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Fort A.P. Hill Soil Permittivity and Conductivity Measurements for the Wide Area Airborne Minefield Detection Program

by Gregory D. Smith and Brian J. Stanton

ARL-TR-3049 September 2003

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ARL-TR-3049 **September 2003**

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
September 2003	Final	October 2002 to March 2003

4. TITLE AND SUBTITLE
Fort A.P. Hill Soil Permittivity and Conductivity Measurements for the Wide Area Airborne Minefield Detection Program

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Gregory D. Smith and Brian J. Stanton

5d. PROJECT NUMBER
3NE4I2

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-SE-RU
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-3049

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
NVESD
AMSEL-RD-NV-ST-CM
10221 Burbeck Rd
Ft. Belvoir, VA 22060

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report discusses the soil permittivity and conductivity measurements at various test environment locations at Ft A.P. Hill for use in modeling predictions in support of the Wide Area Airborne Mine Detection (WAAMD) program. The WAAMD sensor suite consists of four optical sensors and three radar systems. The radars are stand-alone systems operating in different bands: Mirage (300–2800 MHz), Stanford Research Institute (200–450 MHz), and Veridian (8.16–10 GHz). Soil sample sites were located in the drop zone, Lightweight Airborne Mine Detection (LAMD) area, and Area 71A. The drop zone was divided into six test environments. The environments consisted of mines in (1) bare dirt, (2) short grass, and (3) tall grass, and backgrounds of the (4) bare dirt, (5) short grass, and (6) tall grass. The backgrounds were sections of the test sites used to provide ambient data (no mines) of the test environments. Two soil sample sites were selected for characterizing the mines in bare dirt, three sites were selected for characterizing the mines in tall grass, and two sites were selected for characterizing the mines in short grass. A single site was selected for each of the background areas. The LAMD site had four soil sample sites and Area 71A, lane 19 had two soil sample sites. There were 16 soil sample sites selected from these areas. Samples were taken on 21 October 02, 29 October 02, and 25 November 02. Permittivity and conductivity values were measured from 100 to 3000 MHz. The water mass per unit volume of the soil was calculated after completing permittivity and conductivity measurements.

15. SUBJECT TERMS
Permittivity, conductivity, water content, wide area airborne mine detection

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Gregory D. Smith
Unclassified	Unclassified	Unclassified	UL	58	**19b. TELEPHONE NUMBER** *(Include area code)* (301) 394-4849

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

The authors would like to thank E. Sholar from the Fort Belvoir Meteorological Team, Fort A.P. Hill Section, for providing a detailed history of the weather.

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Summary

The U.S. Army Research Laboratory, Adelphi was tasked with providing electromagnetic (EM) modeling predictions for comparison to Wide Area Airborne Minefield Detection (WAAMD) radar measurements. The WAAMD sensor suite consists of four optical sensors and three radar systems. The radars are stand-alone systems operating in different bands: Mirage (300–2800 MHz), Stanford Research Institute (SRI) (200–450 MHz), and Veridian (8.16–10 GHz). The purpose of this project was to measure the permittivity and conductivity of soil at various test environment locations for use in modeling predictions.

The WAAMD data collection site was at Ft. A.P. Hill in Virginia. Various types of fiducials and mines were placed in an assortment of soils representing expected operational conditions. Soil sample sites were located in the drop zone, Lightweight Airborne Mine Detection (LAMD) area, and Area 71A. The drop zone was divided into six test environments. The environments consisted of mines in (1) bare dirt, (2) short grass, and (3) tall grass, and backgrounds of the (4) bare dirt, (5) short grass, and (6) tall grass. The backgrounds were sections of the test sites used to provide ambient data (no mines) of the test environments. Most of the sites in the drop zone contained slopes with gentle hills, resulting in different drainage rates with respect to location. With this in mind, each of the six test environments in the drop zone was further subdivided. Site selection was based on ground contour, variations in soil composition and vegetation, drainage, and water content variations. Soil samples were taken from each site, resulting in cases where multiple soil samples were collected from the same test environment. Two soil sample sites were selected for characterizing the mines in bare dirt, three sites were selected for characterizing the mines in tall grass, and two sites were selected for characterizing the mines in short grass. A single site was selected for each of the background areas. This resulted in the drop zone having 10 soil sample sites. The LAMD site had four soil sample sites and Area 71A, lane 19 had two soil sample sites. Samples were taken on 21 October 2002, 29 October 2002, and 25 November 2002.

Permittivity and conductivity values were measured from 100 to 3000 MHz. The soil samples were packed as tight as possible into the Damaskos liquid/powder cell. Packing the cell with the maximum density of soil provided the most repeatable method for consistently preparing the samples. After completing permittivity and conductivity measurements, the soil was removed from the Damaskos liquid/powder cell and weighed. The sample was then placed in an oven and baked (dried) at 75 ^{o}C for ~10 hr. The soil was removed from the oven and weighed again, and the water mass per unit volume of the soil was calculated.

The variability of the soil permittivity for the different test site locations is summarized in Table I. Some of the variation can be explained by the change in the moisture content of the soils due to the spatial and temporal differences of the soil samples. However, water content does not

Table I. Soil permittivity measurement statistics.

Location	Minimum	Maximum	Mean	Std Dev
Drop Zone				
Bare Dirt	8.19	14.20	10.98	2.06
Short Grass	8.28	19.43	13.87	3.54
Tall Grass	6.59	24.00	14.24	5.33
LAMD				
Sand/Stones	5.05	7.14	6.22	1.07
Sand	14.78	17.45	15.97	1.36
Tall Grass	14.95	21.24	17.64	3.24
Gravel	6.20	7.78	7.11	0.82
Area 71A				
Gravel	6.60	16.39	10.22	5.37
Clay	11.35	15.97	13.08	2.52

solely influence the permittivity; the composition of the soil also plays a role. Generally, an increase in water content resulted in an increase in the real component of the permittivity.

The average water content and delta (Δ) (difference between the maximum and minimum water content) of the bare dirt, short grass, and tall grass were examined. The short grass environment had the highest average water content; however, the tall grass environment had the largest Δ between samples and the most extreme maximum and minimum water content values. The more moisture contained in the soil, the higher the real component of the permittivity.

1. Introduction

The Night Vision and Electronics Sensor Directorate (NVESD) tasked the U.S. Army Research Laboratory (ARL) Adelphi (*1*) with providing electromagnetic (EM) modeling predictions for comparison to Wide Area Airborne Minefield Detection (WAAMD) radar measurements. The WAAMD sensor suite consists of four optical sensors and three radar systems. The radars are stand-alone systems operating in different bands: Mirage (300–2800 MHz), Standford Research Institute (SRI) (200–450 MHz), and Veridian (8.16–10 GHz). Modeling predictions will be completed for each radar system. This presents the research team with a theoretical method of understanding the radar signatures of targets and clutter to develop effective discrimination techniques.

2. Background

2.1 Modeling Techniques

Method of Moment (MoM) modeling techniques will be used to predict the measured radar returns from the targets. In modeling equations, complex permittivity (ε), permeability (μ), and conductivity (σ) are commonly varied parameters. All three parameters are frequency dependent. Permittivity is used for describing dielectric materials and consists of a real component (associated with the dielectric constant) and an imaginary component (associated with energy losses). The permeability is analogous to permittivity with regard to magnetic materials. Conductivity is related to the complex permittivity and describes the loss in a dielectric material. The radar return from the target can be accurately modeled by measuring the ε and σ of the reflecting dielectric media and target. The target may be an unexploded shell or landmine on the surface or buried just under the surface (buried within the dielectric media). The equation used in MoM modeling (*2*) is given as follows:

$$E^S = -j\omega\mu \iint_S K \cdot J ds' - \frac{J}{\varepsilon\omega} \nabla \iint_S K_e \nabla' \cdot J ds' \quad . \tag{1}$$

And the permittivity is described as (*3*),

$$\varepsilon = \varepsilon' - j\varepsilon'' - \frac{j\sigma}{\omega} \quad . \tag{2}$$

2.2 Soil Permittivity and Conductivity for Modeling

The permittivity and conductivity of the fudicals, targets, and surrounding soil are taken into account by the model. The aluminum fudicals and metal mines are treated as perfect conductors. The permittivity and conductivity of plastic targets are determined by referring to tables. The surrounding soil presents a unique problem because of variations in type, consistency, and water content. The water content of the soil strongly influences the permittivity and conductivity. Values will be higher when the soil is moist and lower when dry. In essence, the permittivity and conductivity of the soil are dependent on recent environmental conditions. In order to obtain current test condition values, soil samples were collected and measured prior to the beginning of three flight test periods.

3. Purpose

The purpose of this project was to measure the permittivity and conductivity of soil at various test environment locations for use in MoM modeling predictions.

4. Description of Test Equipment

A Hewlett-Packard (HP) model 8510 Network Analyzer interconnected with a Damaskos Model 3000T Liquid/Powder Cell Permittivity/Permeability Measurement System was used to measure the permittivity and conductivity of the soil samples from 100 to 3000 MHz. A desktop computer containing the Damaskos high-performance software package, called MU-EPSLN, interfaces with the HP8510 Network Analyzer. The software package takes the raw data from the network analyzer and calculates the permittivity and conductivity of the sample.

4.1 Damaskos Model 3000T Liquid/Powder Cell Permittivity/Permeability System

The Damaskos system is a unique and specialized system that measures the complex permittivity, permeability, and conductivity of various types of materials. The system can measure soils, liquids, and solids. The Damaskos system uses a high-performance software package, called MU-EPSLN, to do one- and two-port coax and waveguide measurements using computers running Microsoft Windows or Apple Power PC Macintosh operating systems. The MU-EPSLN program is a complete software package for making S-parameter measurements. Data reduction routines are provided for taking the raw data (S-parameter measurements) and calculating the soil ε, μ, and σ. The program does all the instrument control and real time data processing. A complete description of the HP8510 can be found in reference (*4*) and the description of the Damaskos system can be found in reference (*5*).

4.2 HP8510 Network Analyzer/Damaskos System Overview

A sine wave is applied to the Damaskos system, which contains the soil sample. As the wave travels, it is affected by characteristics of the transmission line, which in this case is the soil. The wave travels along the transmission line essentially unchanged as long as the characteristic impedance of the line remains the same. Because the characteristic impedance of the soil sample is not the same as the transmission line, some of the energy is reflected, some is absorbed, and some is transmitted. The HP8510 network analyzer measures the magnitude and phase of the reflected and transmitted signals (the S-parameters). The S-parameters of a test device are a precise and complete means of describing how a device will respond to a microwave stimulus. For a general two-port device, there are four S-parameters, two of which describe the complex reflection coefficients at each port (S_{11} and S_{22}), and two describing the forward and reverse transmission coefficients (S_{21} and S_{12}). These raw data are imported into the MU-EPSLN program, which calculates the permittivity and conductivity.

5. Soil Sample Site Locations and Conditions

The WAAMD data collection site was at Ft. A.P. Hill, Virginia. Test environment sites were selected to represent different operating conditions. Various types of fiducials and mines were placed at each of the test sites. Soil sample sites were located in the drop zone, Lightweight Airborne Mine Detection (LAMD) area, and Area 71A. There were 16 soil sample sites selected from these areas. Samples were taken on 21 October 2002, 29 October 2002, and 25 November 2002.

5.1 Drop Zone

For purposes of taking soil samples, the drop zone was divided into six test environments. The environments consisted of mines in (1) bare dirt, (2) short grass, and (3) tall grass, and backgrounds of the (4) bare dirt, (5) short grass, and (6) tall grass. The backgrounds were sections of the test sites used to provide ambient data (no mines) of the test environments. Most of the sites contained slopes with gentle hills, resulting in different drainage rates with respect to location. As discussed earlier, the amount of water content in the soil influences the permittivity. With this in mind, each of the six test environments in the drop zone was further subdivided. Site selection was based on ground contour, variations in soil composition and vegetation, drainage, and water content variations. Soil samples were taken from each site, resulting in cases where multiple soil samples were collected from the same test environment. Two soil sample sites were selected for characterizing the mines in bare dirt, two sites were also selected for characterizing the mines in short grass, while three sites were selected for characterizing the mines in tall grass. A single site was selected for each of the background areas. This resulted in the drop zone having 10 soil sample sites.

5.2 Mines in Bare Dirt

The mines in the bare dirt environment were divided into two sites. The intent was to collect one soil sample with high water content and one with low water content. Site 1 was located at one of the highest points in the test environment next to a fiducial (Figures 1 and 2). As can be seen from the figures, the site is located at the top of a slightly sloping hill. This site was selected because the drainage rate in this area was thought to be one of the highest for this test environment, providing a soil sample with low water content. Site 2, also located adjacent to a fiducial, was located in the test environment drainage ditch. Rainwater runoff from most of the test environment passed through this drainage ditch (Figures 3 and 4). This site was selected because of the expected higher water content of the soil. The soil samples from this test environment consisted of a brownish tan sand with clay underneath. Samples from these sites were taken from within the areas marked by the red-orange fluorescent paint.

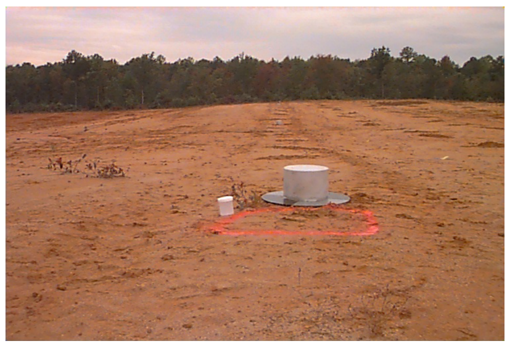

Figure 1. Site 1 mine, bare dirt.

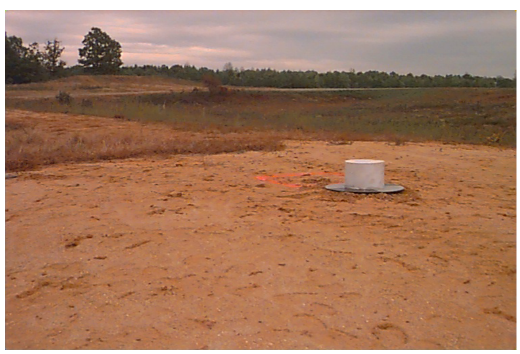

Figure 2. Site 1 mine, bare dirt.

5.3 Background of Bare Dirt

A single site, site 3, was selected for characterizing the soil in the bare dirt background. Site 3 was located midway down a slightly sloping area next to a fiducial (Figures 5 and 6). The entire test environment was located on the side of a slightly sloping hill. Drainage appeared uniform throughout the test environment. Visual surveys did not reveal any pooling water, drainage ditches, or variations in soil composition and vegetation. Based on this, only one site was selected for collecting soil samples from this test environment. The soil samples from this test

environment consisted of a brownish tan sand with clay underneath. Samples from this site were taken from within the area marked by the red-orange fluorescent paint.

Figure 3. Site 2 mine, bare dirt.

Figure 4. Site 2 mine, bare dirt.

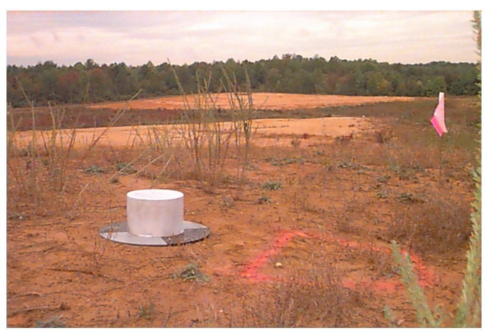

Figure 5. Site 3 background, bare dirt.

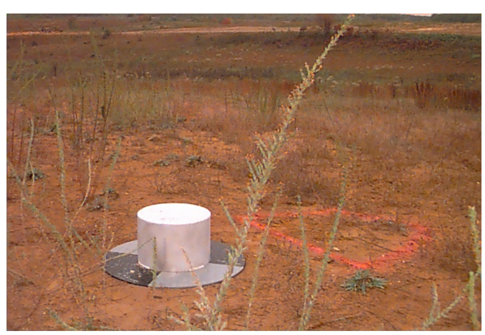

Figure 6. Site 3 background, bare dirt.

5.4 Background of Short Grass

Site 4 was used to characterize the soil for the short grass background. The test environment consisted of a flat, grassy area. The sample site was located adjacent to one of the fiducials (Figures 7 and 8). The sloping hill, observed in the figures, is located beyond the short grass background boundary. Drainage appeared to be uniform throughout the short grass test environment. Visual surveys did not reveal any pooling water, drainage ditches, or drier than "normal" locations. Based on this, only one site was selected for collecting soil samples from this test environment. Vegetation consisted of thick grass ~4–6 in high. The soil was uniform throughout the test environment. The soil samples from this test environment consisted of topsoil on the surface with brown clay underneath. The samples contained roots, but grass was not included. Samples from this site were taken from within the area marked by the red-orange fluorescent paint.

Figure 7. Site 4 background, short grass.

Figure 8. Site 4 background, short grass.

5.5 Background of Tall Grass

Site 5 was used to characterize the soil for the tall grass background. The test environment consisted of a flat, grassy area. The soil sample site was located ~2 m from one of the fiducials, marked by the red-orange fluorescent stake (Figures 9 and 10). Drainage appeared to be uniform throughout the tall grass test environment. Visual surveys did not reveal any pooling water, drainage ditches, or drier or wetter than normal locations. Based on this, only one site was selected for collecting soil samples from this test environment. Vegetation consisted of thick

Figure 9. Site 5 background, tall grass.

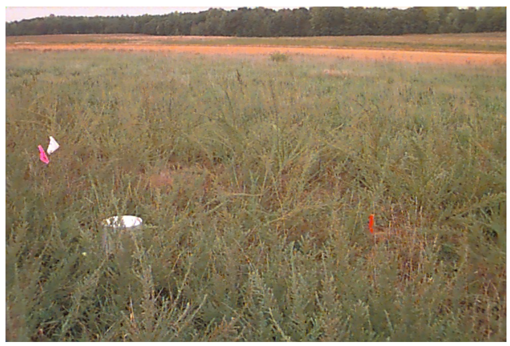

Figure 10. Site 5 background, tall grass.

grass ~7–12 in high and single stem weeds with small leaves. The soil was uniform throughout the test environment. The soil samples from this test environment consisted of a brownish clay soil and some roots. Grass was not included with the sample.

5.6 Mines in Short Grass

The mines in the short grass environment were divided into two sites. The majority of the test environment consisted of a flat, grassy area. The exception to this was on the eastern side of the test environment, which had a sloping hill. Site 6 (Figure 11) was located in the flat grassy area while site 7 (Figure 12) was located on the slope. Two sites were selected to characterize the soil in this environment because of anticipated water content variations between locations. Drainage appeared to be uniform throughout the flat grassy area test environment. Visual surveys did not reveal any pooling water, drainage ditches, or drier than normal locations at either site. The drainage rate for the slope was significantly greater than the flat grassy area. Vegetation at both sites consisted of thick grass ~4–6 in high. The soil was uniform throughout the test environment. The soil samples from this test environment consisted of topsoil on the surface with brown clay and roots underneath. Grass was not included with the sample.

Figure 11. Site 6 mine, short grass.

Figure 12. Site 7 mine, short grass.

5.7 Mines in Tall Grass

The mines in the tall grass environment were divided into three sites. The test environment was located on a sloping, grassy area. The highest point was located on the northwestern corner and the lowest point was at the southeastern corner. Drainage was not uniform throughout the test environment. Visual surveys revealed pooling water in the southeast corner. Additionally, variations in the quantity of vegetation varied between locations within the test environment. Vegetation in the northwest corner was sparse due to the close proximity of the dirt road. This area can best be described as the shoulder of the road. Vegetation in the center of the test environment consisted of thick grass ~7–12 in high and single stem weeds with small leaves. The vegetation in the southeast corner consisted of brown grass, probably from the long periods of being submerged in water, ~7–12 in tall. Three sites were selected to characterize the soil in this environment because of anticipated water content variations between locations. Site 8 was selected in the northwest corner (Figure 13) to collect soil from an area with a high drainage rate. Site 9 was located at the center of the test environment (Figure 14). This site was selected because the water content of the soil was anticipated to be between the northwest corner and the southeast corner. Finally, site 10 was located in the southeast corner (Figure 15). This was the lowest point in the test environment and had the highest water content. The soil samples from this test environment consisted of brown clay and some roots. Grass was not included with the sample. Samples from sites 8 and 10 were taken from within the area marked by the red-orange fluorescent paint. Samples from site 9 were taken adjacent to the stake located in the lower center of Figure 14.

Figure 13. Site 8 mine, tall grass.

Figure 14. Site 9 mine, tall grass.

Figure 15. Site 10 mine, tall grass.

5.8 LAMD Area

For the purpose of taking soil samples, the LAMD area was divided into four test environments. The environments consisted of mines in (1) sand/stone, (2) sand, (3) tall grass, and (4) gravel. All of the environments were located in controlled lanes. Drainage rates did not appear to vary with location; so only one site per environment (or lane) was selected to characterize the soil. The tall grass lane consisted of topsoil with thick grass ~7–12 in tall. Soil samples were taken of the topsoil, which included the roots. Grass was not included in the sample. There was no vegetation present in the other three lanes. Site 11 was in the sand/stone lane (Figure 16); site 12 was in the sand lane (Figure 17); site 13 was in the tall grass lane (Figure 18); and site 14 was in the gravel lane (Figure 19). Samples from these sites were taken from within the area marked by the red-orange fluorescent paint.

Figure 16. Site 11 mine, sand/stone.

Figure 17. Site 12 mine, sand.

Figure 18. Site 13 mine, tall grass.

Figure 19. Site 14 mine, gravel.

5.9 Area 71A

For the purpose of taking soil samples, Area 71A was divided into two test environments. The environments consisted of mines in (1) gravel and (2) clay. All of the environments were located in lane 19. Drainage rates did not appear to vary with location; so only one site per environment (or lane) was selected to characterize the soil. Vegetation was not present in either lane. Site 15 was in the gravel (Figures 20 and 21), and site 16 was in the clay (Figures 20 and 21). Samples from these sites were taken from within the area marked by the red-orange fluorescent paint.

Figure 20. Sites 15, 16 mine, gravel and clay.

Figure 21. Sites 15, 16 mine, gravel and clay.

5.10 Soil Collection Summary

A summary of the soil sample sites can be found in Table 1. The sample column provides the sample number. Three sets of each sample were collected to characterize the soil over the course of the flight test program. The location provides the site where the samples were taken. DZ is the drop zone, LAMD is the Lightweight Airborne Mine Detection area, and 71A is Area 71A, lane 19. The latitude and longitude were measured using a differential Global Positioning System (GPS). Values are presented in north (N) or west (W) in degrees, minutes, and seconds. The Area Description provides a general description of the test environment. The last three columns, located on the right of the table, provide the date and time that the sample sets were collected. As can be seen, samples were collected on 21 and 29 October 2002 and 25 November 2002. These times were selected because flight test periods were scheduled to begin on or about these dates.

Table 1. Ft A.P. Hill soil sample site collection summary.

Sample	Location	Latitude (N d m s.s)	Longitude (W d m s.s)	Area Description	Date 21 Oct 2002 Set 1 Time	Date 29 Oct 2002 Set 2 Time	Date 25 Nov 2002 Set 3 Time
1	DZ	38 10 06.590	77 22 53.182	Mine, bare dirt	1121	0945	1000
2	DZ	38 10 04.954	77 22 51.487	Mine, bare dirt	1125	0947	1003
3	DZ	38 10 05.047	77 22 46.298	Bkgrd, bare dirt	1130	0953	1005
4	DZ	38 09 54.867	77 22 38.447	Bkgrd, short grass	1147	0957	1008
5	DZ	38 09 38.724	77 22 28.140	Bkgrd, tall grass	1209	1030	1020
6	DZ	38 09 37.450	77 22 24.718	Mine, short grass	1217	1003	1028
7	DZ	38 09 37.673	77 22 22.318	Mine, short grass	1225	1007	1031
8	DZ	38 09 36.363	77 22 25.698	Mine, tall grass	1240	1012	1034
9	DZ	38 09 34.672	77 22 24.822	Mine, tall grass	1243	1019	1037
10	DZ	38 09 32.523	77 22 24.518	Mine, tall grass	1247	1022	1040
11	LAMD	38 08 48.102	77 21 35.291	Mine, sand/stones	1300	1044	1048
12	LAMD	38 08 48.206	77 21 35.872	Mine, sand	1303	1041	1050
13	LAMD	38 08 48.538	77 21 35.690	Mine, tall grass	1306	1043	1052
14	LAMD	38 08 48.805	77 21 34.681	Mine, gravel	1310	1045	1053
15	71A	38 06 15.385	77 11 59.252	Mine, gravel	1400	1130	1127
16	71A	38 06 15.348	77 11 59.198	Mine, clay	1402	1131	1128

Table 2 provides a summary of the weather conditions at Ft A.P. Hill at the time the soil samples were collected. The values for temperature, humidity, dew point, wind, pressure, and visibility are averages for the period over which the soil samples were collected. For example, the temperature for sample set 1 is the average temperature that occurred between 1121 and 1402. The conditions describe the weather at the time the samples were collected, where MC is mostly cloudy. The maximum and minimum temperatures are the highs and lows for the day. The last 24, 48, and 72 hr are a summary of events for the previous days, where OC is overcast.

Table 2. Ft A.P. Hill soil sample set weather conditions.

	21 Oct 2002	**29 Oct 2002**	**25 Nov 2002**
Sample Set	**1**	**2**	**3**
Temperature (ºF)	56.3	44.3	53.6
Humidity (%)	57.5	70	55.8
Dew point (ºF)	41.5	34.8	38.0
Wind (mph)	6.2	8.4	0.0
Pressure (in)	30.12	30.10	30.11
Visibility (mi)	10.0	4.8	10.0
Conditions	MC	Rain	Clear
Max temp (ºF)	59.0	48.2	69.8
Min temp (ºF)	44.6	41.0	30.2
Last			
24 hr	Rain	Rain	Clear
48 hr	Clear	OC	Clear
72 hr	Rain	Rain	Mist

6. Test Methods and Procedures

Soil samples with a diameter and depth of ~20 cm were collected using a typical, garden variety shovel. The samples were placed top-down in hermetically sealed plastic jars with twist-on lids. The diameter of a jar is ~17 cm with a depth of ~19 cm. The lids have a pressure-sensitive foam liner with a 0.05-cm thickness. Excess soil was returned to the site.

The HP8510 Network Analyzer and Damaskos Liquid/Powder Cell Permittivity/Permeability System were calibrated prior to soil measurements. The accuracy of the calibration was verified by measuring the permittivity of air, which is ~1 + j0. Additionally, the air measurements were repeated periodically, usually after each soil sample, to provide a high degree of confidence that the soil measurements were consistent. Any variations in the permittivity of more than ± 0.02 in the real or imaginary part over the frequency band of 100–3000 MHz resulted in a system recalibration.

Permittivity and conductivity measurements from 100 MHz to 3000 MHz were made with the soil samples packed as tight as possible into the Damaskos liquid/powder cell. Packing the cell with the maximum density of soil provided the most repeatable method for consistently preparing the samples. Additionally, only minor differences in the permittivity and conductivity were measured between tightly and loosely packed soil. For example, tightly packed soil would have a permittivity of 12, while the loosely packed soil would have a value of 11.6. The impact of packing density was investigated using 3 of the 16 samples.

After completing permittivity and conductivity measurements, the soil was removed from the Damaskos liquid/powder cell and weighed. The sample was then placed in an oven and baked (dried) at 75 ^{o}C for ~10 hr. The soil was removed from the oven and weighted again. The water mass per unit volume of the soil was calculated using equation 3,

$$\frac{Mass_{sample,wet} - Mass_{sample,dry}}{Volume_{sample}} \quad . \tag{3}$$

7. Chronology

The following is a chronology of this project's major milestones:

- Test environments subdivided into sites for soil collection — 21 October 2002
- Soil sample set 1 collected from Ft. A.P. Hill — 21 October 2002

- Soil sample set 1 analyzed at ARL 25–31 October 2002
- Soil sample set 2 collected from Ft. A.P. Hill 29 October 2002
- Soil sample set 2 analyzed at ARL 31 October 2002–5 November 2002
- Soil sample set 3 collected from Ft. A.P. Hill 25 November 2002
- Soil sample set 3 analyzed at ARL 26 November 2002–9 January 2003
- WAAMD soil analysis report 10 January 2003–14 February 2003

8. Results

8.1 Soil Measurement Results and Trends

The soil samples were characterized by measuring the permittivity, conductivity, and water content. The permittivity and conductivity of the samples were measured from 100 to 3000 MHz in 7.25-MHz steps, resulting in 401 data points across the frequency band. The permittivity and conductivity plots are contained in Figures 22–37. Referring to the figures, the soil site location indicates the area from which the soil sample was taken. The area description provides a general description of the test environment. The latitude and longitude of each site are also given. The permittivity plots are located on the left, and the conductivity plots are on the right. Each plot is labeled with the site number, date of sample, and grams per cubic centimeter (g/cm^3) of water. The relative permittivity plots contain both the real component (blue line) and imaginary component (magenta line). The conductivity plots are shown by the blue line and are in units of Siemens per meter (S/m).

Examination of the plots revealed a roll-off occurring between 100 and 500 MHz. The three sets of sample 5 raw data were processed in a number of different ways to determine if the roll-off was data related or an artifact from the calibration. In all cases, the results were essentially the same, indicating the roll-off was a characteristic of the soil and not a calibration artifact. Additionally, research of the literature revealed similar results in this frequency range (*6*, *7*).

Soil Site Location: Drop Zone **Latitude:** N 38 10 06.590
Area Description: Mine, Bare Dirt **Longitude:** W 77 22 53.182

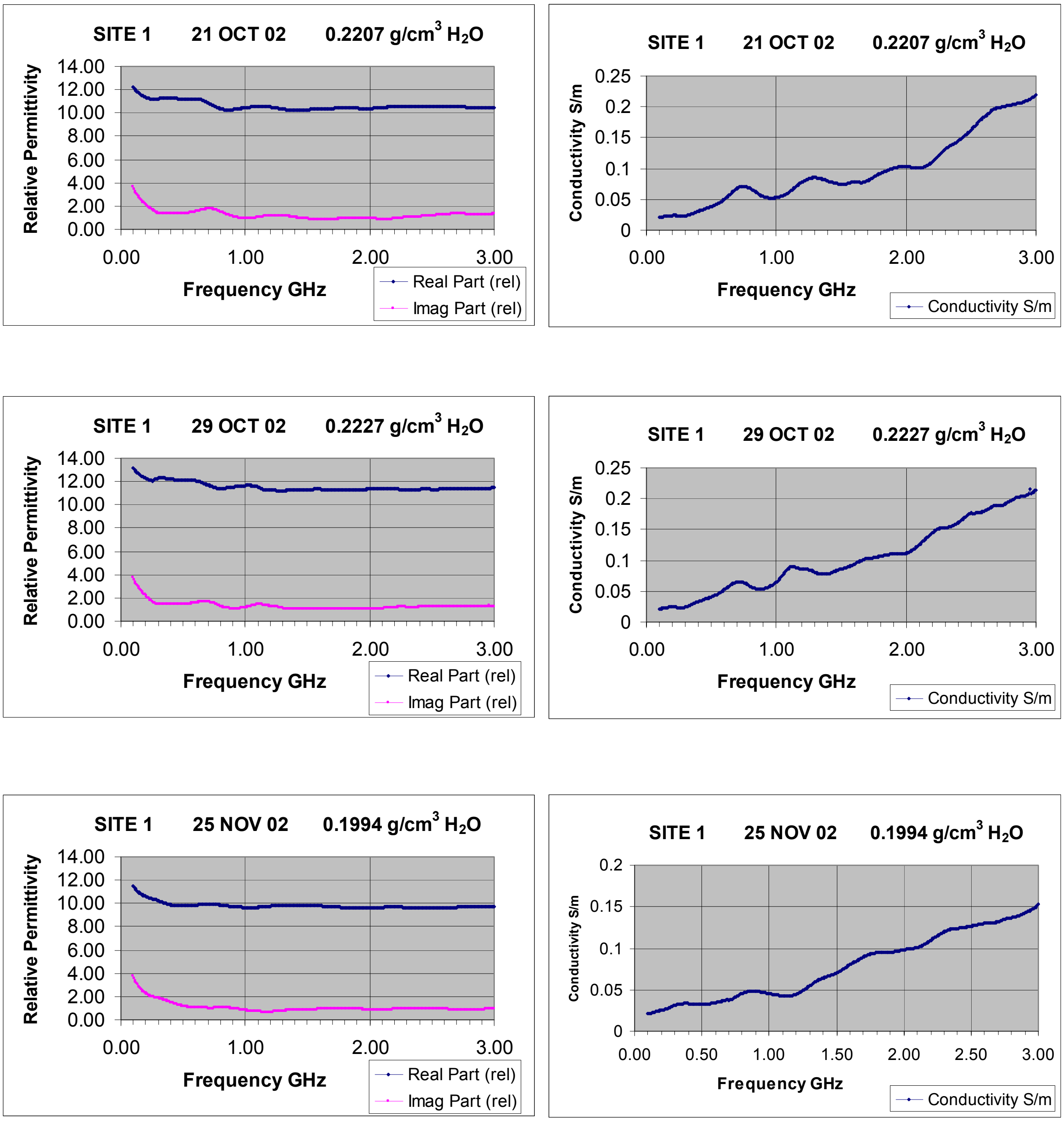

Figure 22. Site 1 permittivity and conductivity measurements.

Soil Site Location:	Drop Zone	**Latitude:**	N 38 10 04.954
Area Description:	Mine, Bare Dirt	**Longitude:**	W 77 22 51.487

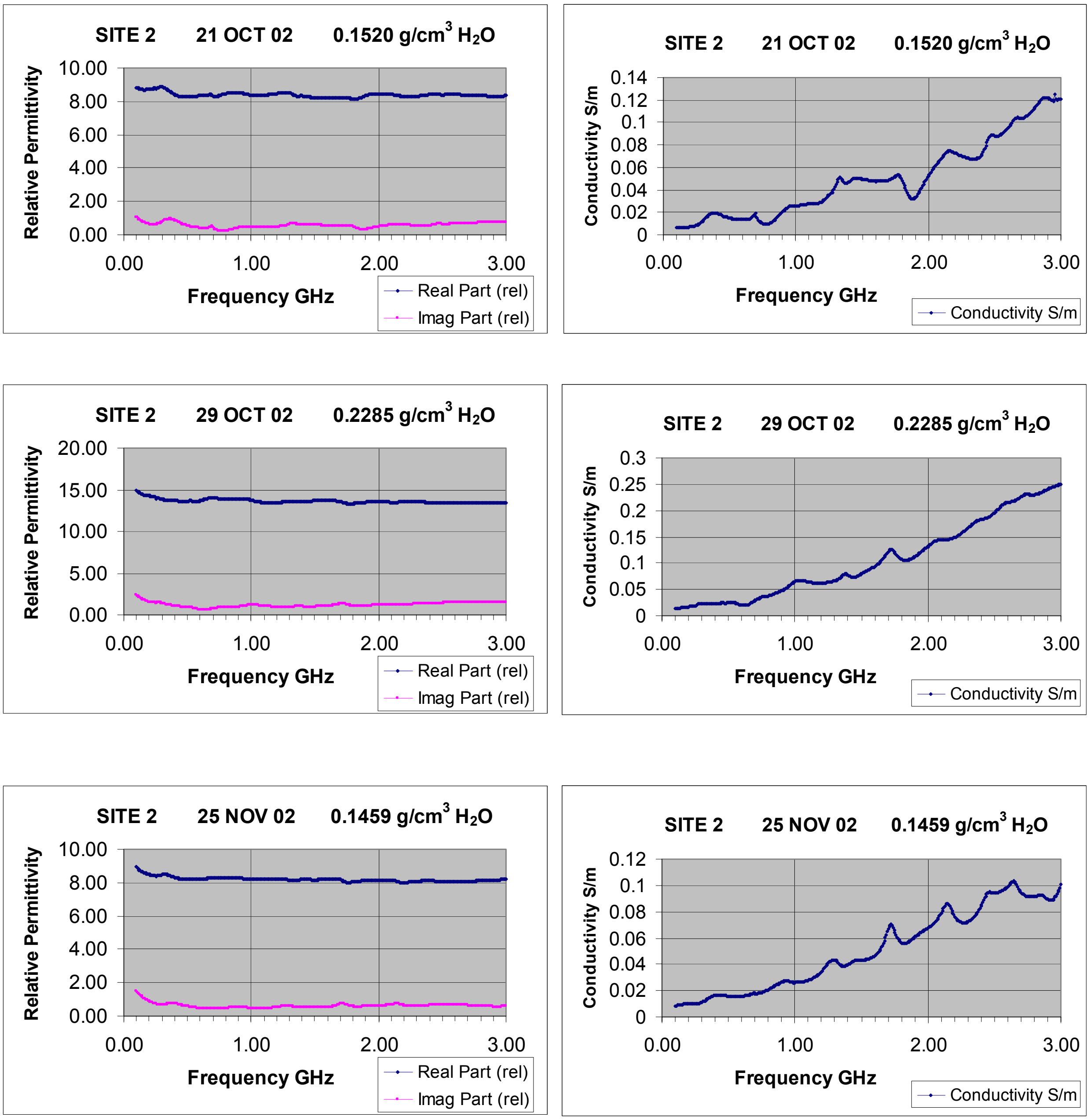

Figure 23. Site 2 permittivity and conductivity measurements.

Soil Site Location: Drop Zone **Latitude:** N 38 10 05.047
Area Description: Background, Bare Dirt **Longitude:** W 77 22 46.298

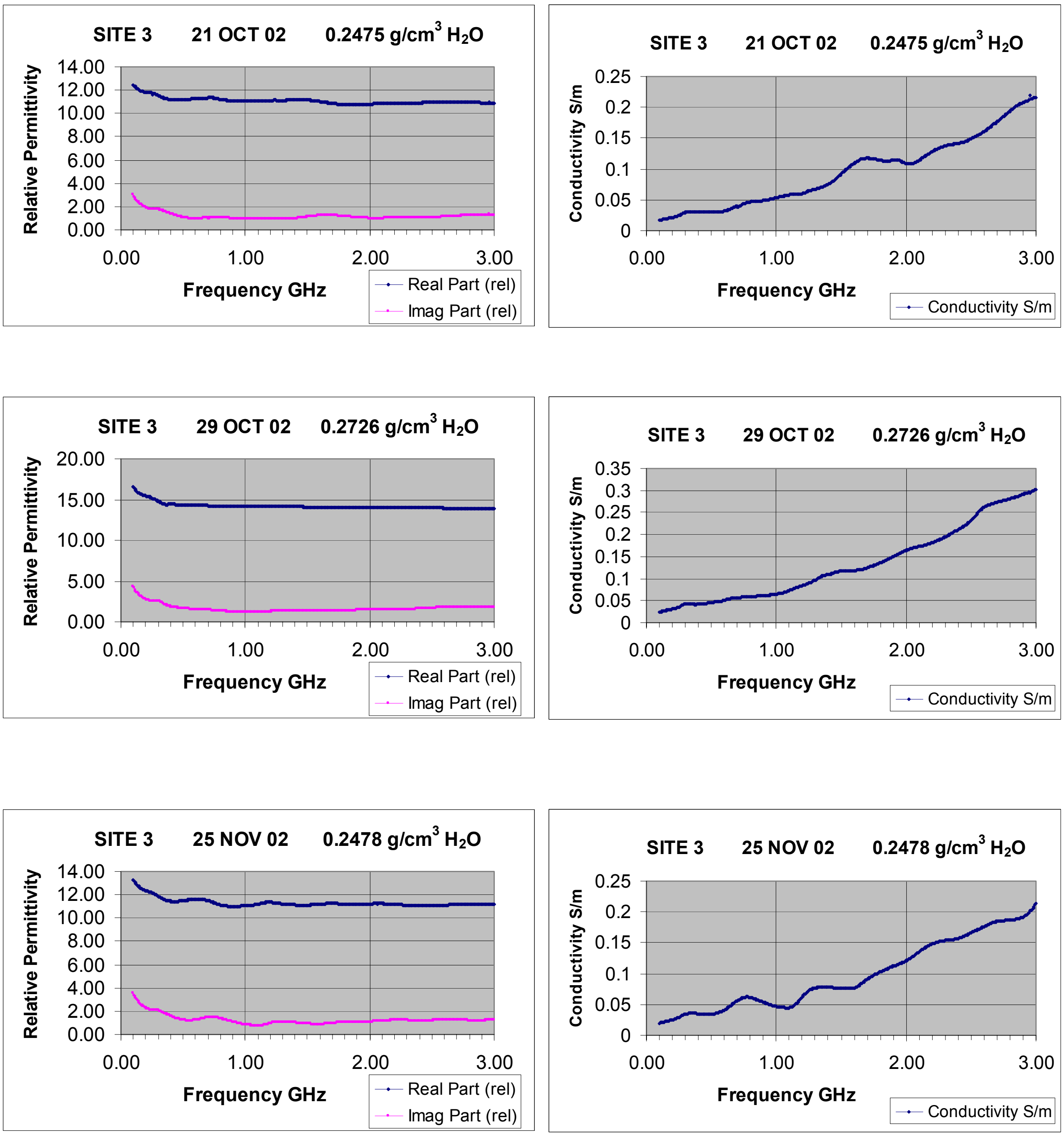

Figure 24. Site 3 permittivity and conductivity measurements.

Soil Site Location: Drop Zone **Latitude:** N 38 09 54.867
Area Description: Background, Short Grass **Longitude:** W 77 22 38.447

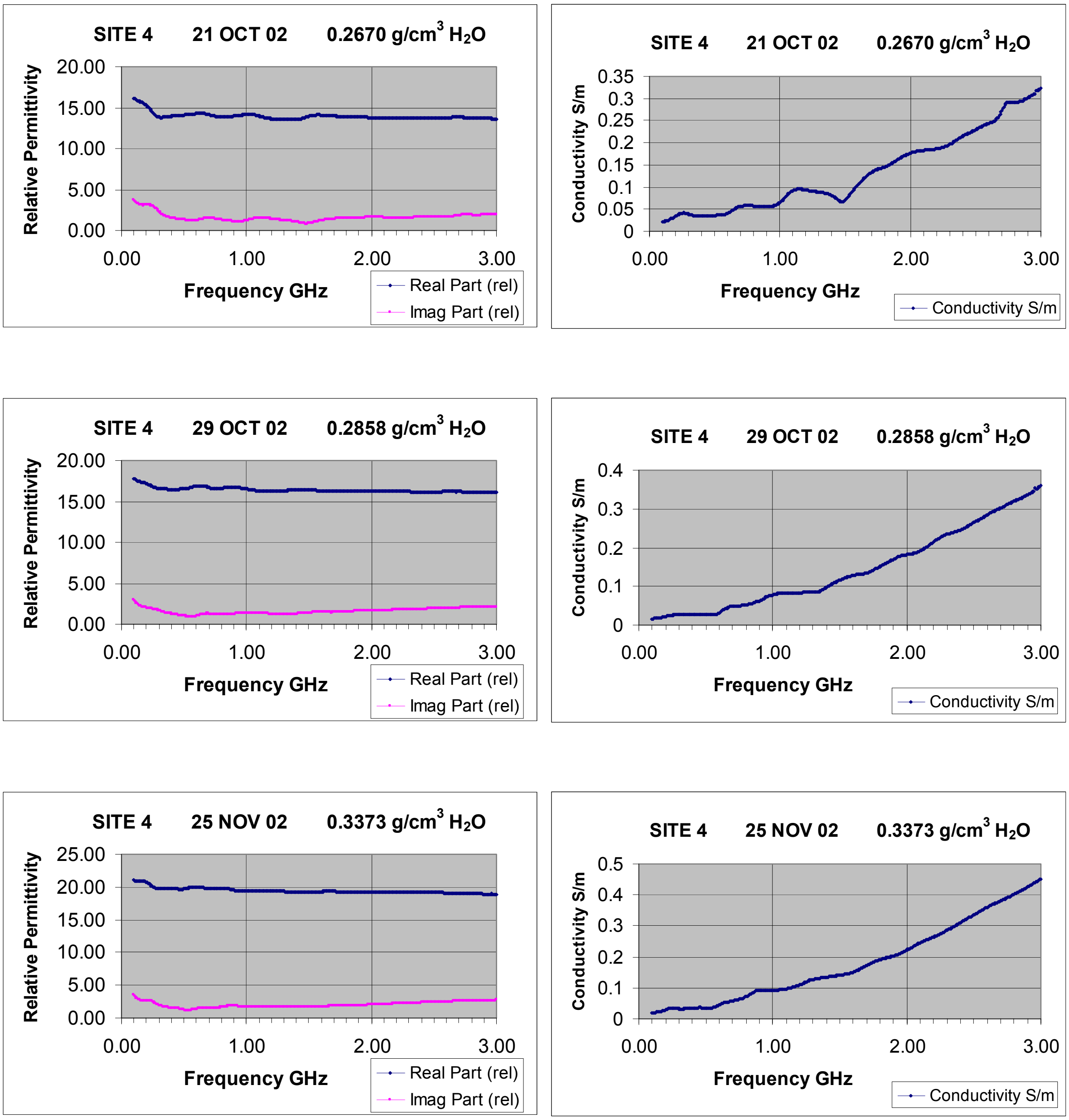

Figure 25. Site 4 permittivity and conductivity measurements.

Soil Site Location:	Drop Zone	**Latitude:**	N 38 09 38.724
Area Description:	Background, Tall Grass	**Longitude:**	W 77 22 28.140

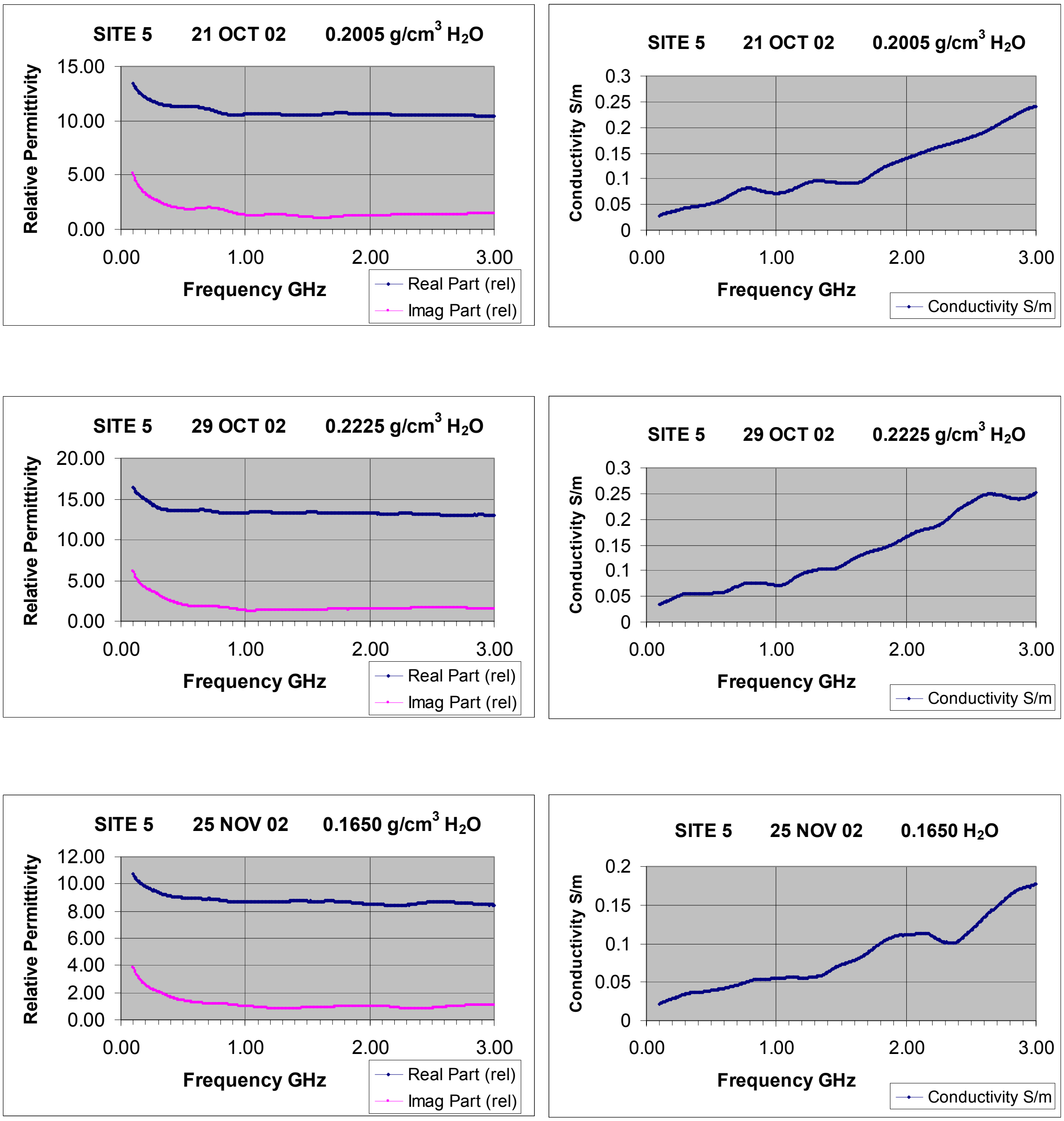

Figure 26. Site 5 permittivity and conductivity measurements.

Soil Site Location: Drop Zone **Latitude:** N 38 09 37.450
Area Description: Mine, Short Grass **Longitude:** W 77 22 24.718

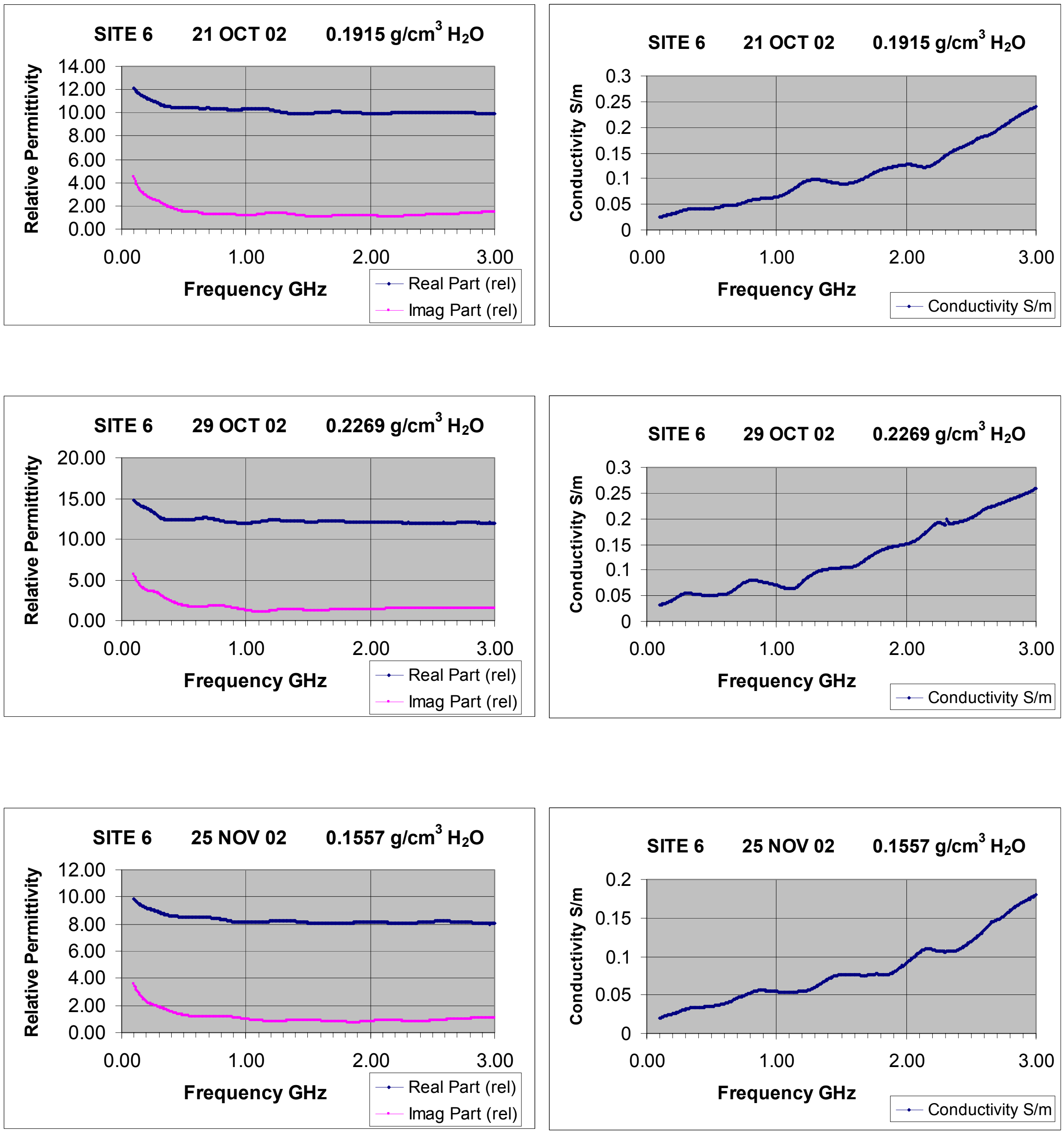

Figure 27. Site 6 permittivity and conductivity measurements.

Soil Site Location: Drop Zone **Latitude:** N 38 09 37.673
Area Description: Mine, Short Grass **Longitude:** W 77 22 22.318

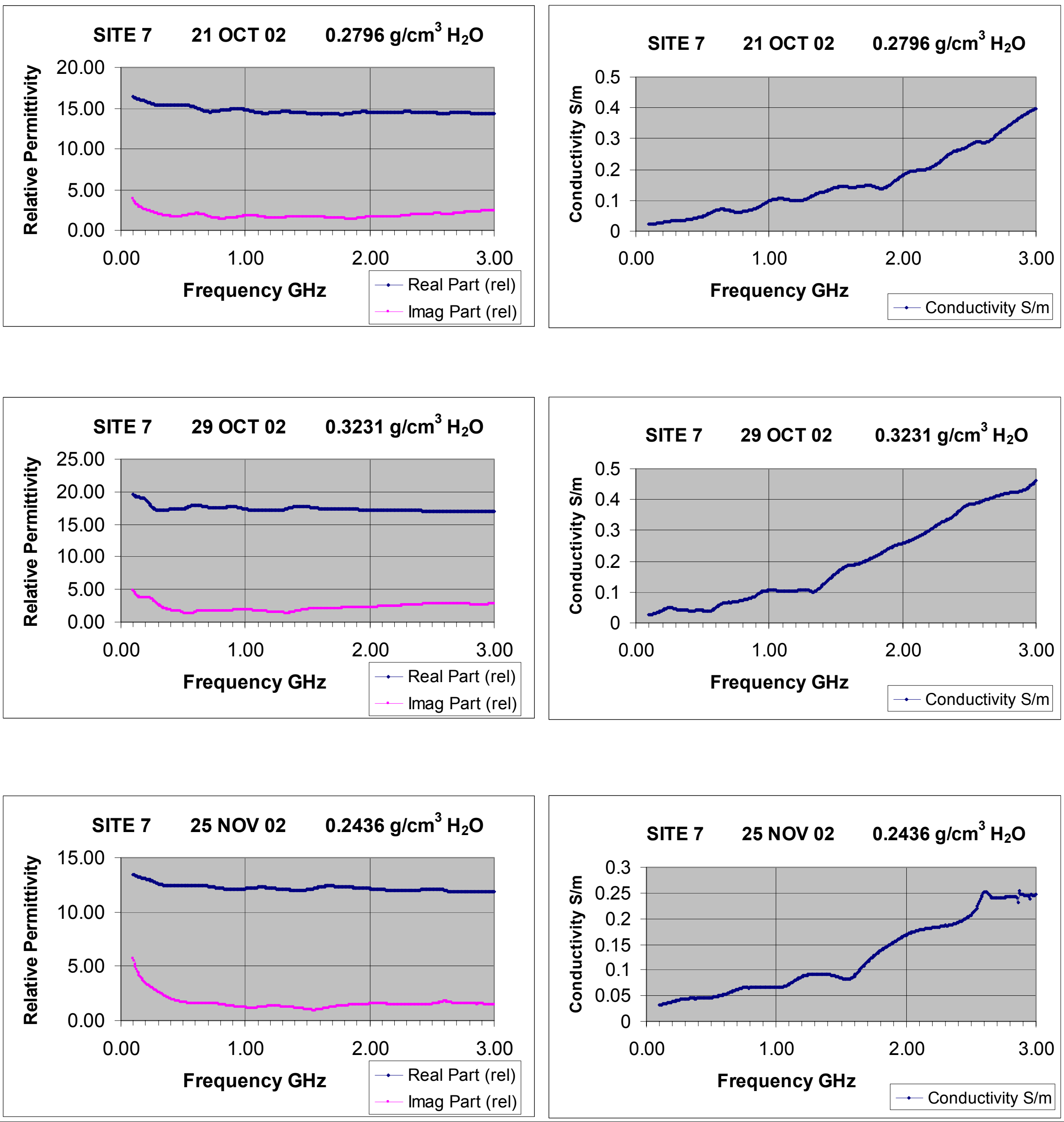

Figure 28. Site 7 permittivity and conductivity measurements.

Soil Site Location: Drop Zone **Latitude:** N 38 09 36.363
Area Description: Mine, Tall Grass **Longitude:** W 77 22 25.698

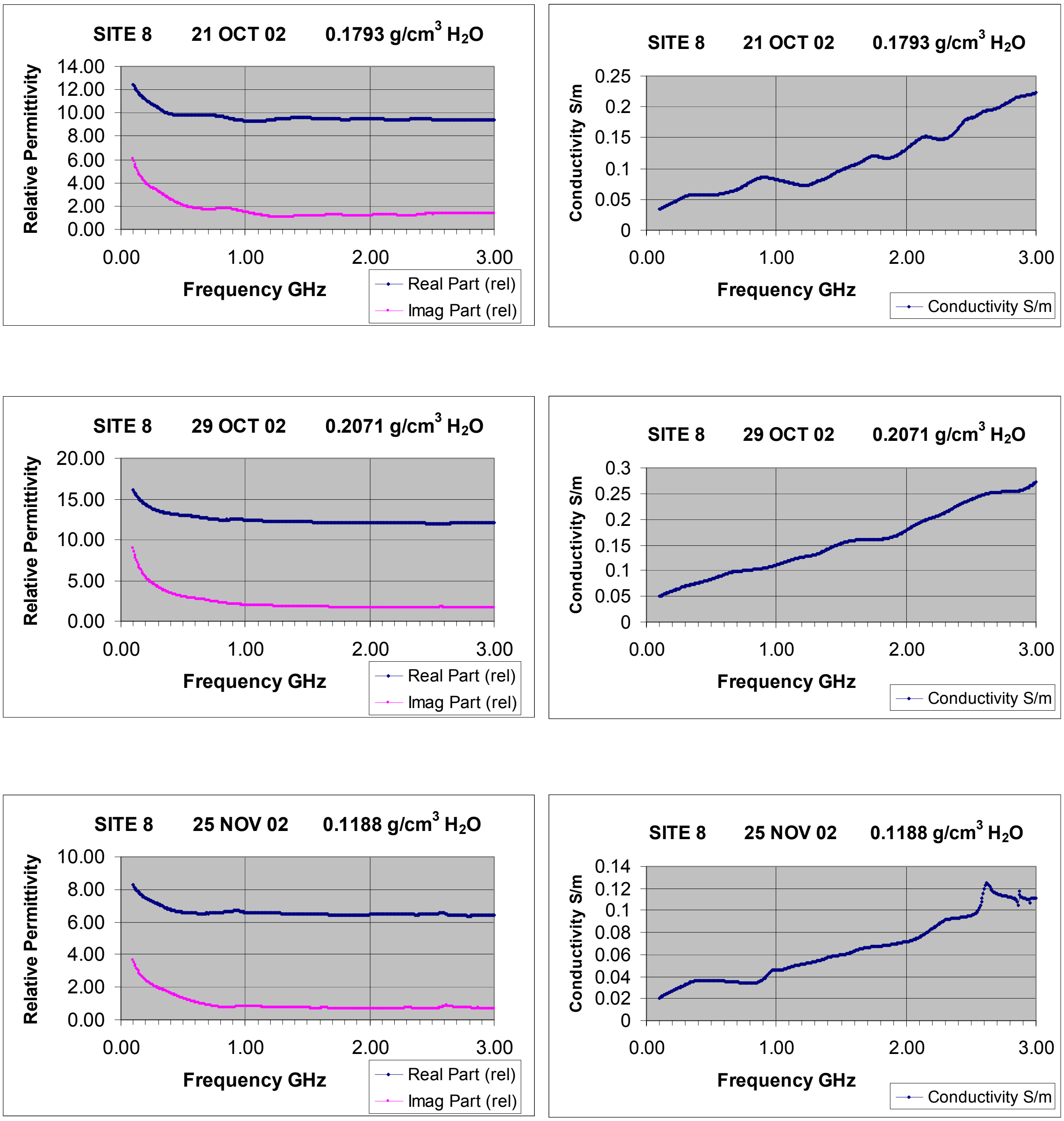

Figure 29. Site 8 permittivity and conductivity measurements.

Soil Site Location:	Drop Zone	**Latitude:**	N 38 09 34.672
Area Description:	Mine, Tall Grass	**Longitude:**	W 77 22 24.822

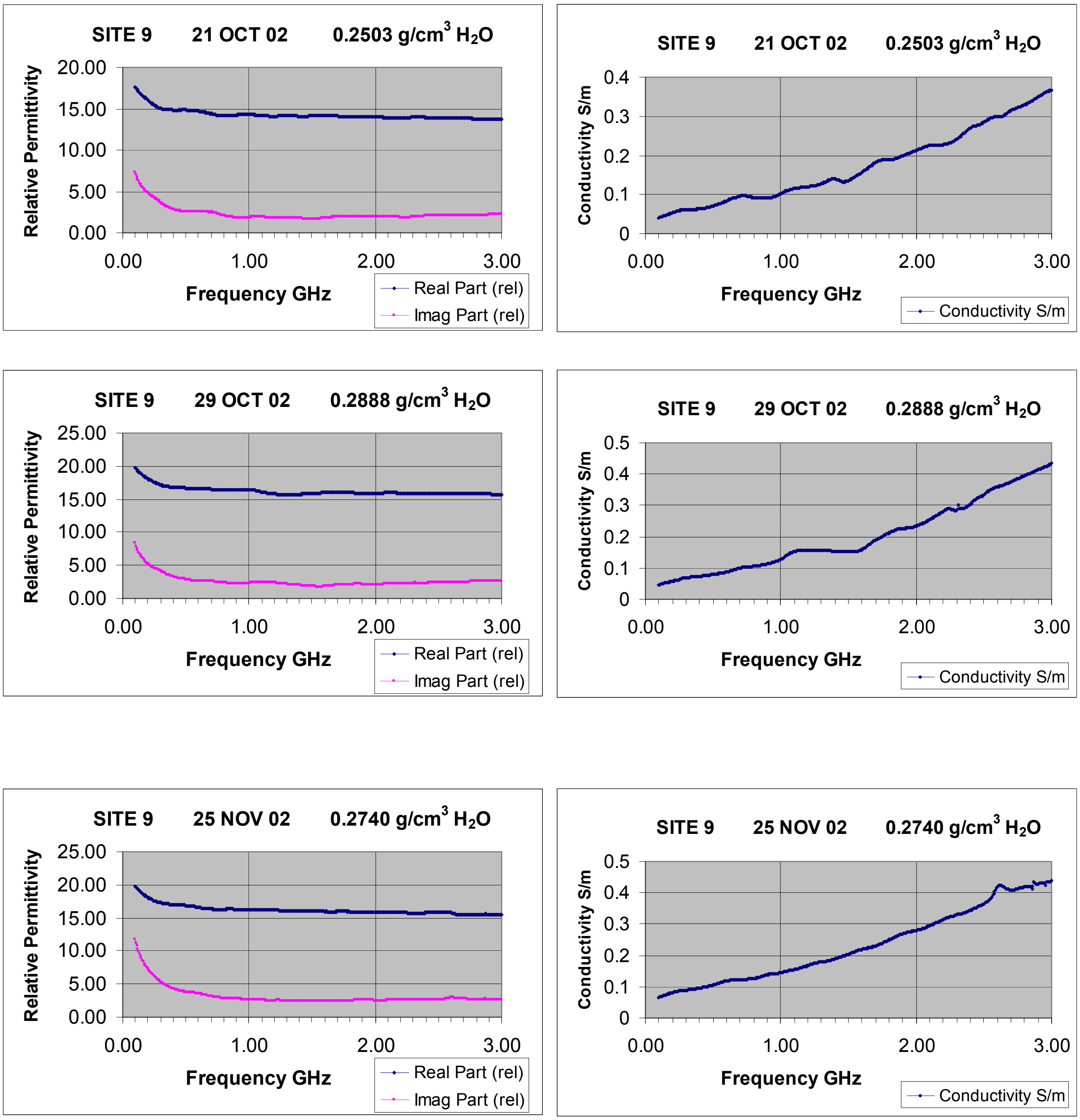

Figure 30. Site 9 permittivity and conductivity measurements.

Soil Site Location:	Drop Zone	**Latitude:**	N 38 09 32.523
Area Description:	Mine, Tall Grass	**Longitude:**	W 77 22 24.518

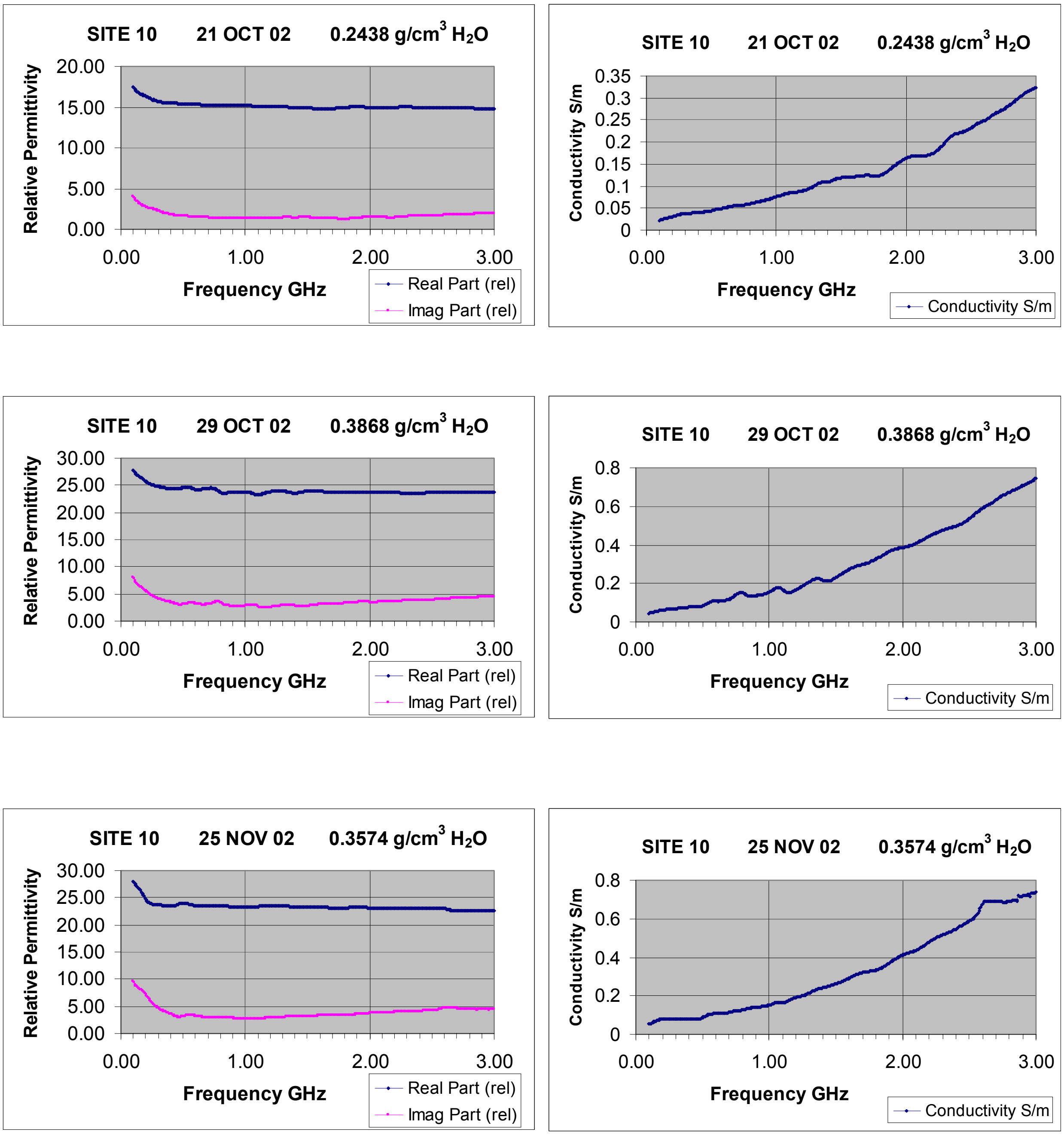

Figure 31. Site 10 permittivity and conductivity measurements.

Soil Site Location: LAMD **Latitude:** N 38 08 48.102
Area Description: Mine, Sand/Stones **Longitude:** W 77 21 35.291

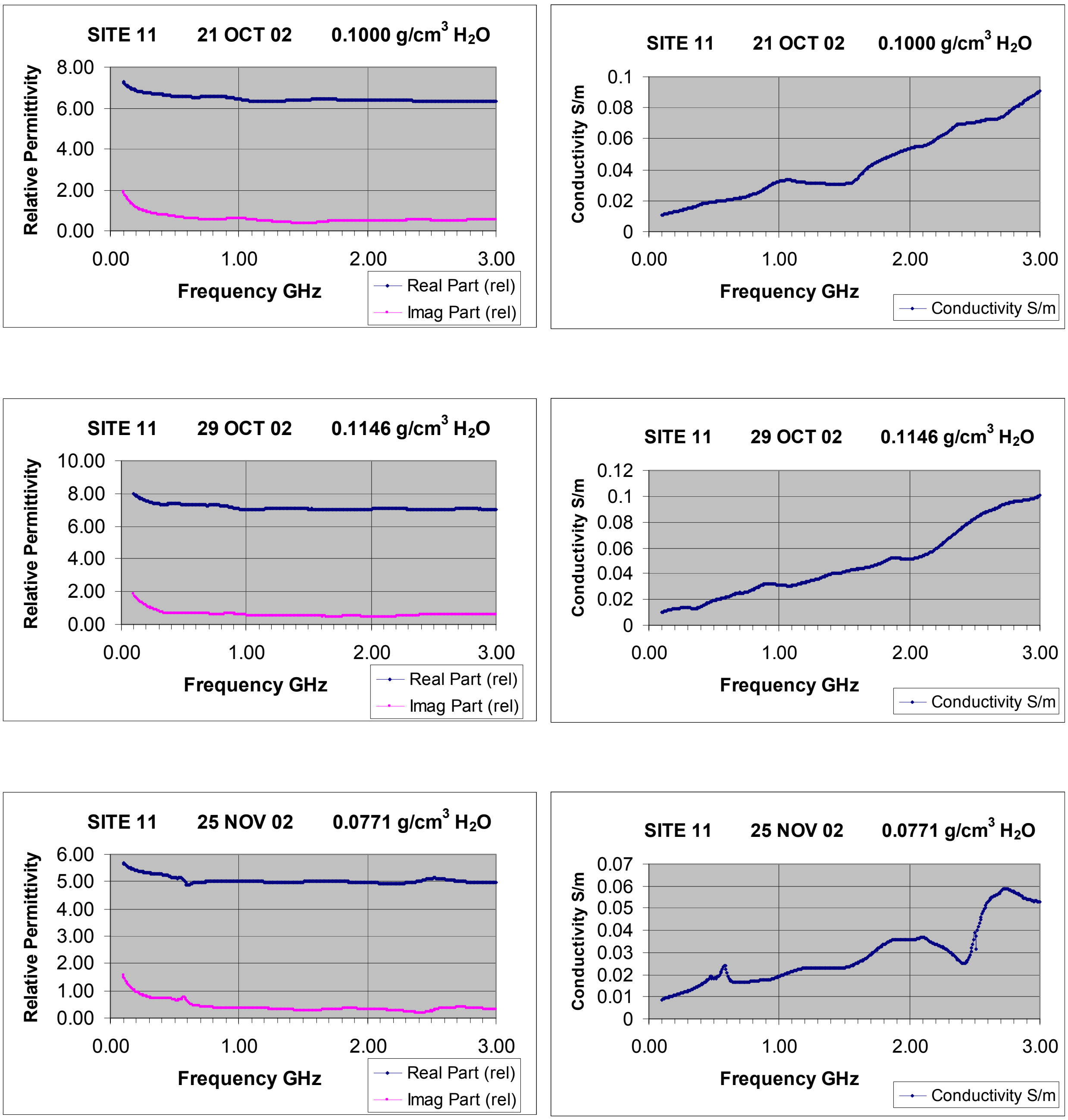

Figure 32. Site 11 permittivity and conductivity measurements.

Soil Site Location: LAMD **Latitude:** N 38 08 48.206
Area Description: Mine, Sand **Longitude:** W 77 21 35.872

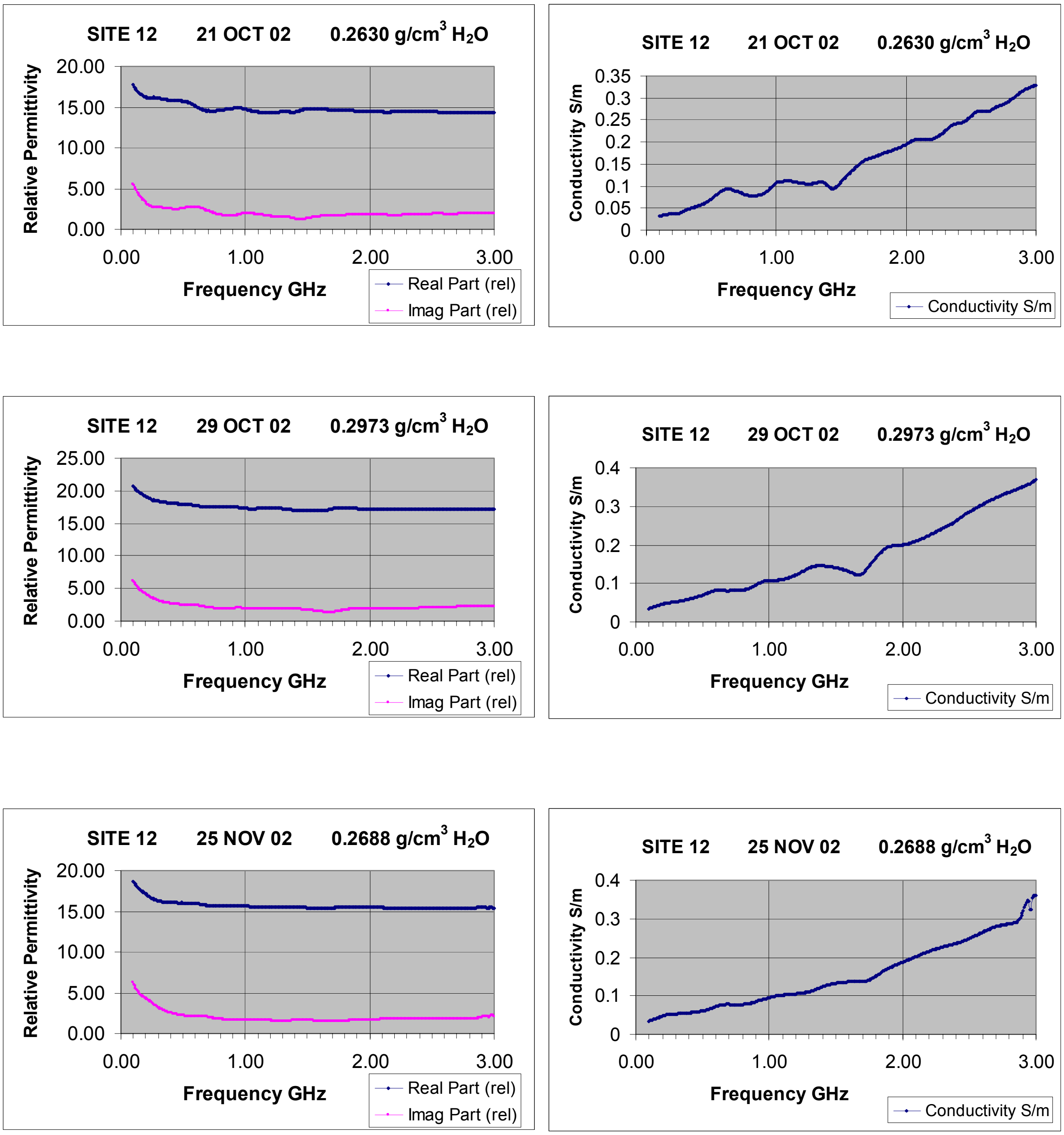

Figure 33. Site 12 permittivity and conductivity measurements.

Soil Site Location: LAMD **Latitude:** N 38 08 48.538
Area Description: Mine, Tall Grass **Longitude:** W 77 21 35.690

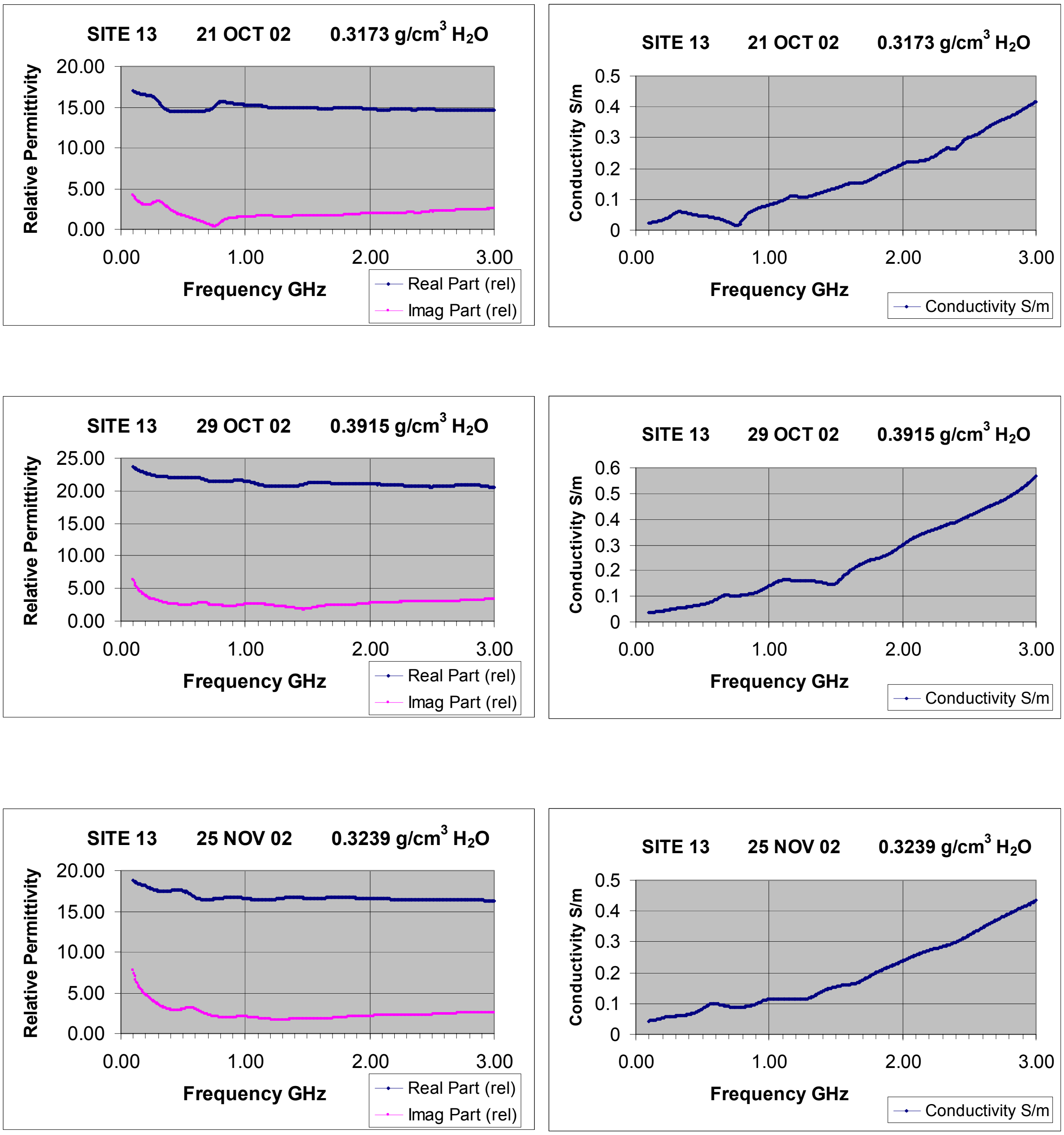

Figure 34. Site 13 permittivity and conductivity measurements.

Soil Site Location: LAMD **Latitude:** N 38 08 48.805
Area Description: Mine, Gravel **Longitude:** W 77 21 34.681

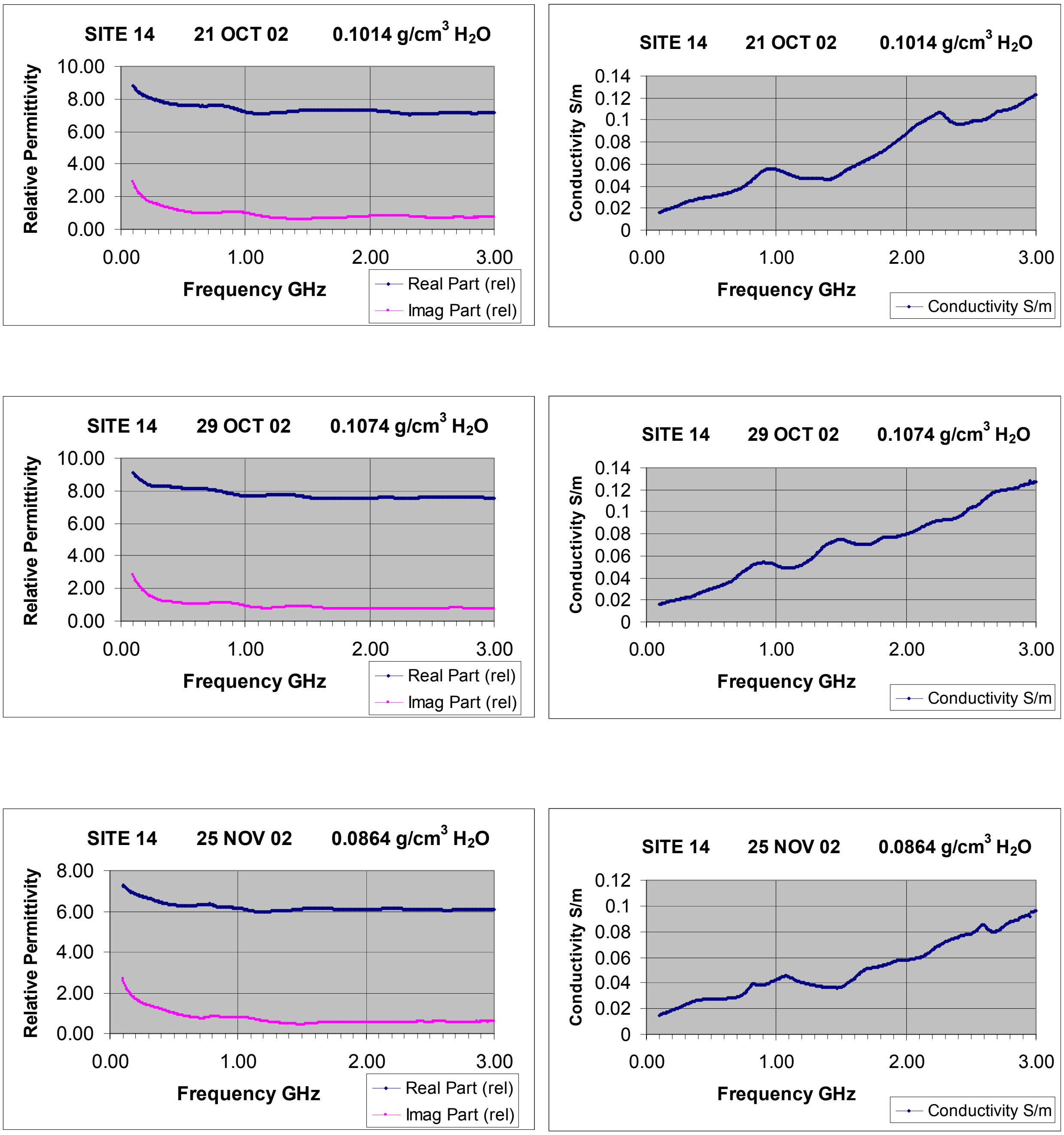

Figure 35. Site 14 permittivity and conductivity measurements.

Soil Site Location: Area 71A **Latitude:** N 38 06 15.385
Area Description: Mine, Gravel **Longitude:** W 77 11 59.252

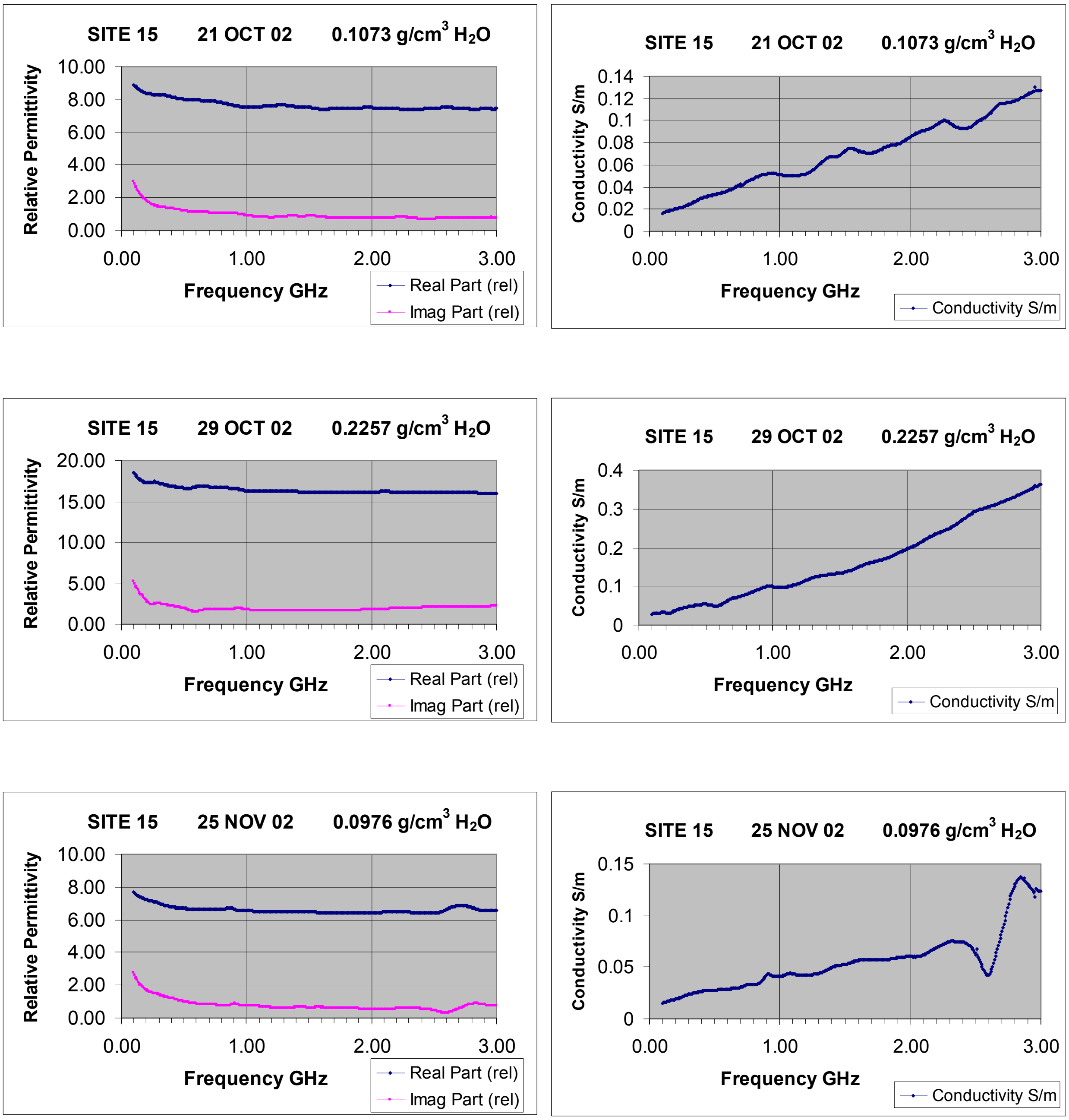

Figure 36. Site 15 permittivity and conductivity measurements.

Soil Site Location: Area 71A **Latitude:** N 38 06 15.348
Area Description: Mine, Clay **Longitude:** W 77 11 59.198

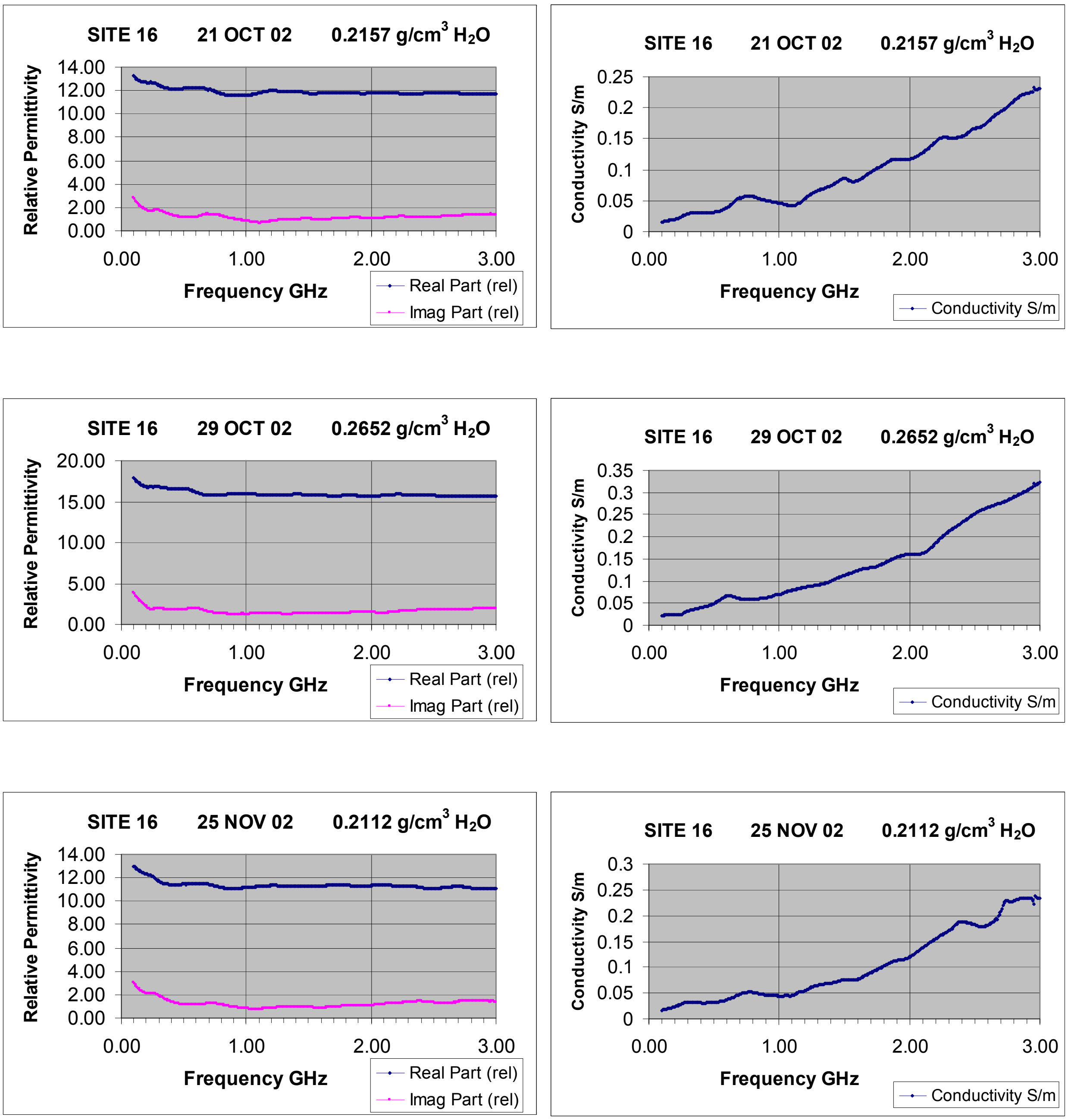

Figure 37. Site 16 permittivity and conductivity measurements.

The plots reveal the influence of soil water content on the permittivity and the conductivity. This influence is also tabulated in Table 3 for easy comparison. Generally, as shown in the plots and summarized in Table 3, an increase in water content resulted in an increase in the real component of the permittivity. The water content and the minimum, maximum, and average values of the permittivity (both real and imaginary components) and conductivity are contained in Table 3 for each soil sample. These values are based on measurements from 100 to 3000 MHz. The average permittivity and conductivity values were calculated across the frequency band to provide a "starting" point for the MoM modeling predictions. The average values also proved useful in providing an insight into the data trends.

Table 3. Permittivity and conductivity measurements from 100 to 3000 MHz.

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
1	21 Oct 2002	10.2–12.2	10.62	0.8–3.6	1.22	0.02–0.22	0.097	0.2207
1	29 Oct 2002	11.2–13.2	11.55	1.0–3.7	1.30	0.02–0.22	0.104	0.2227
1	25 Nov 2002	9.6–11.5	9.80	0.7–3.7	1.04	0.02–0.15	0.078	0.1994
2	21 Oct 2002	8.1–8.9	8.39	0.2–1.1	0.56	0.01–0.13	0.050	0.1520
2	29 Oct 2002	13.3–14.9	13.63	0.6–2.4	1.17	0.01–0.25	0.106	0.2285
2	25 Nov 2002	8.0–8.9	8.19	0.4–1.5	0.60	0.01–0.10	0.051	0.1459
3	21 Oct 2002	10.8–12.5	11.09	0.9–3.0	1.16	0.02–0.22	0.096	0.2475
3	29 Oct 2002	13.8–16.5	14.20	1.2–4.3	1.62	0.02–0.30	0.134	0.2726
3	25 Nov 2002	11.0–13.3	11.31	0.7–3.5	1.23	0.02–0.21	0.098	0.2478
4	21 Oct 2002	13.6–16.2	13.95	0.8–3.7	1.57	0.02–0.32	0.133	0.2670
4	29 Oct 2002	16.1–17.8	16.41	0.9–2.9	1.57	0.02–0.36	0.145	0.2858
4	25 Nov 2002	18.9–21.0	19.43	1.1–3.5	1.98	0.02–0.45	0.182	0.3373
5	21 Oct 2002	10.4–13.4	10.80	1.0–5.1	1.56	0.03–0.24	0.116	0.2005
5	29 Oct 2002	13.0–16.4	13.40	1.2–6.2	1.78	0.03–0.25	0.134	0.2225
5	25 Nov 2002	8.4–10.7	8.78	0.8–3.9	1.14	0.02–0.18	0.084	0.1650
6	21 Oct 2002	9.9–12.1	10.22	1.0–4.4	1.39	0.02–0.24	0.107	0.1915
6	29 Oct 2002	12.0–14.8	12.28	1.0–5.7	1.67	0.03–0.26	0.126	0.2269
6	25 Nov 2002	8.0–9.8	8.28	0.7–3.6	1.09	0.02–0.18	0.081	0.1557
7	21 Oct 2002	14.2–16.4	14.67	1.3–3.8	1.82	0.02–0.40	0.157	0.2796
7	29 Oct 2002	16.9–19.5	17.38	1.2–4.9	2.23	0.03–0.46	0.199	0.3231
7	25 Nov 2002	11.9–13.4	12.21	0.9–5.8	1.61	0.03–0.25	0.125	0.2436
8	21 Oct 2002	9.3–12.5	9.66	1.0–6.1	1.62	0.03–0.22	0.115	0.1793
8	29 Oct 2002	12.0–16.1	12.45	1.6–8.9	2.25	0.05–0.27	0.157	0.2071
8	25 Nov 2002	6.4–8.3	6.59	0.6–3.7	0.94	0.02–0.13	0.065	0.1188
9	21 Oct 2002	13.7–17.6	14.27	1.6–7.3	2.26	0.04–0.37	0.174	0.2503
9	29 Oct 2002	15.7–19.9	16.22	1.8–8.3	2.60	0.05–0.43	0.202	0.2888
9	25 Nov 2002	15.5–19.8	16.21	2.4–11.8	3.14	0.07–0.44	0.232	0.2740

Table 3. Permittivity and conductivity measurements from 100 to 3000 MHz (cont'd).

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
10	21 Oct 2002	14.8–17.4	15.13	1.2–4.0	1.62	0.02–0.32	0.135	0.2438
10	29 Oct 2002	23.2–27.7	24.00	2.4–8.1	3.55	0.04–0.75	0.309	0.3868
10	25 Nov 2002	22.6–28.1	23.36	2.6–9.6	3.80	0.05–0.74	0.328	0.3574
11	21 Oct 2002	6.3–7.3	6.46	0.4–1.9	0.57	0.01–0.09	0.043	0.1000
11	29 Oct 2002	7.0–8.0	7.14	0.5–1.8	0.61	0.01–0.10	0.048	0.1146
11	25 Nov 2002	4.9–5.7	5.05	0.2–1.6	0.41	0.01–0.06	0.029	0.0771
12	21 Oct 2002	14.3–17.7	14.78	1.2–5.6	1.98	0.03–0.33	0.156	0.2630
12	29 Oct 2002	16.9–20.7	17.45	1.3–6.2	2.14	0.03–0.37	0.169	0.2973
12	25 Nov 2002	15.3–18.7	15.67	1.4–6.3	1.99	0.03-0.36	0.154	0.2688
13	21 Oct 2002	14.4–17.0	14.95	0.3–4.2	1.90	0.01–0.42	0.166	0.3173
13	29 Oct 2002	20.5–23.7	21.24	1.8–6.4	2.74	0.04–0.57	0.237	0.3915
13	25 Nov 2002	16.3–18.8	16.73	1.6–7.8	2.42	0.04–0.43	0.192	0.3239
14	21 Oct 2002	7.1–8.8	7.36	0.6–2.9	0.90	0.02–0.12	0.066	0.1014
14	29 Oct 2002	7.5–9.1	7.78	0.7–2.8	0.93	0.02–0.13	0.070	0.1074
14	25 Nov 2002	6.0–7.3	6.20	0.4–2.7	0.73	0.01–0.10	0.051	0.0864
15	21 Oct 2002	7.4–8.9	7.66	0.7–3.0	0.95	0.02–0.13	0.070	0.1073
15	29 Oct 2002	16.0–18.5	16.39	1.5–5.2	1.95	0.03–0.36	0.164	0.2257
15	25 Nov 2002	6.4–7.7	6.60	0.3–2.7	0.77	0.02–0.14	0.055	0.0976
16	21 Oct 2002	11.6–13.2	11.91	0.7–2.8	1.18	0.02–0.23	0.099	0.2157
16	29 Oct 2002	15.6–17.9	15.97	1.2–3.8	1.61	0.02–0.32	0.138	0.2652
16	25 Nov 2002	11.0–13.0	11.35	0.7–3.0	1.22	0.02–0.24	0.103	0.2112

8.2 Water Content Results

The results were sorted based on increasing water content in Table 4. The water content and associated minimum, maximum, and average values of the permittivity (both real and imaginary components) and conductivity are tabulated in Table 4. The spread or difference between the "wettest" and "driest" sample was 314.4 mg/cm^3. As shown in Table 4, the water per unit volume is strictly increasing among all the soil samples; however, the permittivity is not strictly increasing. Water content does not solely influence the permittivity; the composition of the soil also plays a role.

Table 4. Water content comparison of soil samples.

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
11	25 Nov 2002	4.9–5.7	5.05	0.2–1.6	0.41	0.01–0.06	0.029	0.0771
14	25 Nov 2002	6.0–7.3	6.20	0.4–2.7	0.73	0.01–0.10	0.051	0.0864
15	25 Nov 2002	6.4–7.7	6.60	0.3–2.7	0.77	0.02–0.14	0.055	0.0976

Table 4. Water content comparison of soil samples (cont'd).

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
11	21 Oct 2002	6.3–7.3	6.46	0.4–1.9	0.57	0.01–0.09	0.043	0.1000
14	21 Oct 2002	7.1–8.8	7.36	0.6–2.9	0.90	0.02–0.12	0.066	0.1014
15	21 Oct 2002	7.4–8.9	7.66	0.7–3.0	0.95	0.02–0.13	0.070	0.1073
14	29 Oct 2002	7.5–9.1	7.78	0.7–2.8	0.93	0.02–0.13	0.070	0.1074
11	29 Oct 2002	7.0–8.0	7.14	0.5–1.8	0.61	0.01–0.10	0.048	0.1146
8	25 Nov 2002	6.4–8.3	6.59	0.6–3.7	0.94	0.02–0.13	0.065	0.1188
2	25 Nov 2002	8.0–8.9	8.19	0.4–1.5	0.60	0.01–0.10	0.051	0.1459
2	21 Oct 2002	8.1–8.9	8.39	0.2–1.1	0.56	0.01–0.13	0.050	0.1520
6	25 Nov 2002	8.0–9.8	8.28	0.7–3.6	1.09	0.02–0.18	0.081	0.1557
5	25 Nov 2002	8.4–10.7	8.78	0.8–3.9	1.14	0.02–0.18	0.084	0.1650
8	21 Oct 2002	9.3–12.5	9.66	1.0–6.1	1.62	0.03–0.22	0.115	0.1793
6	21 Oct 2002	9.9–12.1	10.22	1.0–4.4	1.39	0.02–0.24	0.107	0.1915
1	25 Nov 2002	9.6–11.5	9.80	0.7–3.7	1.04	0.02–0.15	0.078	0.1994
5	21 Oct 2002	10.4–13.4	10.80	1.0–5.1	1.56	0.03–0.24	0.116	0.2005
8	29 Oct 2002	12.0–16.1	12.45	1.6–8.9	2.25	0.05–0.27	0.157	0.2071
16	25 Nov 2002	11.0–13.0	11.35	0.7–3.0	1.22	0.02–0.24	0.103	0.2112
16	21 Oct 2002	11.6–13.2	11.91	0.7–2.8	1.18	0.02–0.23	0.099	0.2157
1	21 Oct 2002	10.2–12.2	10.62	0.8–3.6	1.22	0.02–0.22	0.097	0.2207
5	29 Oct 2002	13.0–16.4	13.40	1.2–6.2	1.78	0.03–0.25	0.134	0.2225
1	29 Oct 2002	11.2–13.2	11.55	1.0–3.7	1.30	0.02–0.22	0.104	0.2227
15	29 Oct 2002	16.0–18.5	16.39	1.5–5.2	1.95	0.03–0.36	0.164	0.2257
6	29 Oct 2002	12.0–14.8	12.28	1.0–5.7	1.67	0.03–0.26	0.126	0.2269
2	29 Oct 2002	13.3–14.9	13.63	0.6–2.4	1.17	0.01–0.25	0.106	0.2285
7	25 Nov 2002	11.9–13.4	12.21	0.9–5.8	1.61	0.03–0.25	0.125	0.2436
10	21 Oct 2002	14.8–17.4	15.13	1.2–4.0	1.62	0.02–0.32	0.135	0.2438
3	21 Oct 2002	10.8–12.5	11.09	0.9–3.0	1.16	0.02–0.22	0.096	0.2475
3	25 Nov 2002	11.0–13.3	11.31	0.7–3.5	1.23	0.02–0.21	0.098	0.2478
9	21 Oct 2002	13.7–17.6	14.27	1.6–7.3	2.26	0.04–0.37	0.174	0.2503
12	21 Oct 2002	14.3–17.7	14.78	1.2–5.6	1.98	0.03–0.33	0.156	0.2630
16	29 Oct 2002	15.6–17.9	15.97	1.2–3.8	1.61	0.02–0.32	0.138	0.2652
4	21 Oct 2002	13.6–16.2	13.95	0.8–3.7	1.57	0.02–0.32	0.133	0.2670
12	25 Nov 2002	15.3–18.7	15.67	1.4–6.3	1.99	0.03–0.36	0.154	0.2688
3	29 Oct 2002	13.8–16.5	14.20	1.2–4.3	1.62	0.02–0.30	0.134	0.2726
9	25 Nov 2002	15.5–19.8	16.21	2.4–11.8	3.14	0.07–0.44	0.232	0.2740
7	21 Oct 2002	14.2–16.4	14.67	1.3–3.8	1.82	0.02–0.40	0.157	0.2796
4	29 Oct 2002	16.1–17.8	16.41	0.9–2.9	1.57	0.02–0.36	0.145	0.2858
9	29 Oct 2002	15.7–19.9	16.22	1.8–8.3	2.60	0.05–0.43	0.202	0.2888
12	29 Oct 2002	16.9–20.7	17.45	1.3–6.2	2.14	0.03–0.37	0.169	0.2973
13	21 Oct 2002	14.4–17.0	14.95	0.3–4.2	1.90	0.01–0.42	0.166	0.3173
7	29 Oct 2002	16.9–19.5	17.38	1.2–4.9	2.23	0.03–0.46	0.199	0.3231
13	25 Nov 2002	16.3–18.8	16.73	1.6–7.8	2.42	0.04–0.43	0.192	0.3239
4	25 Nov 2002	18.9–21.0	19.43	1.1–3.5	1.98	0.02–0.45	0.182	0.3373
10	25 Nov 2002	22.6–28.1	23.36	2.6–9.6	3.80	0.05–0.74	0.328	0.3574
10	29 Oct 2002	23.2–27.7	24.00	2.4–8.1	3.55	0.04–0.75	0.309	0.3868
13	29 Oct 2002	20.5–23.7	21.24	1.8–6.4	2.74	0.04–0.57	0.237	0.3915

The samples taken on 25 November 2002, which had been "drying" for at least 72 hr prior to collection (Table 2), were not the sample sets with the least amount of water per unit volume as expected. Likewise, the sample sets from 21–29 October 2002, which had both been subject to rain one and three days prior to collection (Table 2), did not have approximately equal amounts of water per unit volume. This is likely due to the sloping terrain described in section 5.

8.3 Comparison of Drop Zone Mine and Background Sites

8.3.1 Bare Dirt

The variability of the soil measurements from the bare dirt test environment was examined. The bare dirt environment is composed of sites 1, 2, and 3. Sites 1 and 2 contained mines while site 3 had no mines (ambient). The permittivity, conductivity, and water content measurements from these sites are contained in Table 5.

Table 5. Comparison between mines and background bare dirt environment.

Site	Date	Area Description	Real ε Avg.	Imag ε Avg.	σ Avg.	H_2O (g/cm^3)
1	21 Oct 2002	Mine, bare dirt	10.62	1.22	0.097	0.2207
1	29 Oct 2002	Mine, bare dirt	11.55	1.30	0.104	0.2227
1	25 Nov 2002	Mine, bare dirt	9.80	1.04	0.078	0.1994
2	21 Oct 2002	Mine, bare dirt	8.39	0.56	0.050	0.1520
2	29 Oct 2002	Mine, bare dirt	13.63	1.17	0.106	0.2285
2	25 Nov 2002	Mine, bare dirt	8.19	0.60	0.051	0.1459
3	21 Oct 2002	Bkgrd, bare dirt	11.09	1.16	0.096	0.2475
3	29 Oct 2002	Bkgrd, bare dirt	14.20	1.62	0.134	0.2726
3	25 Nov 2002	Bkgrd, bare dirt	11.31	1.23	0.098	0.2478

Results reveal that the soil samples from the background site (site 3) always had higher water content then the two sample sites that had mines. Site 3 had 26.8 mg/cm^3 more water than site 1 on 21 October 2002, 49.9 mg/cm^3 more on 29 October 2002, and 48.4 mg/cm^3 more on 25 November 2002. With regard to site 2, site 3 had 95.5 g/cm^3 more water on 21 October 2002, 44.1 mg/cm^3 more on 29 October 2002, and 101.9 mg/cm^3 more on 25 November 2002. Although the parameters measured at site 3 should not be used in modeling the targets, it may be useful in characterizing the clutter backscatter.

The average conductivity and permittivity at sites 1 and 3 increased with increasing water content. Average permittivity real values at site 2 also increased with increasing water content. However, this was not the case for site 2 conductivity and average imaginary permittivity values. A possible explanation for this may be due to measurement errors of the Damaskos system.

A permittivity histogram of the bare dirt environment is contained in Figure 38. The bins are based on the average permittivity real component values. The x-axis is marked such that the number denotes the upper limit of the bin. For example, site 2's average real permittivity values, 8.39 and 8.19, are contained in the same bin, which would have an upper limit of 9.00. The minimum, maximum, mean, and standard deviation values, contained in Figure 38, are based on the real, average permittivity values and not the bin values.

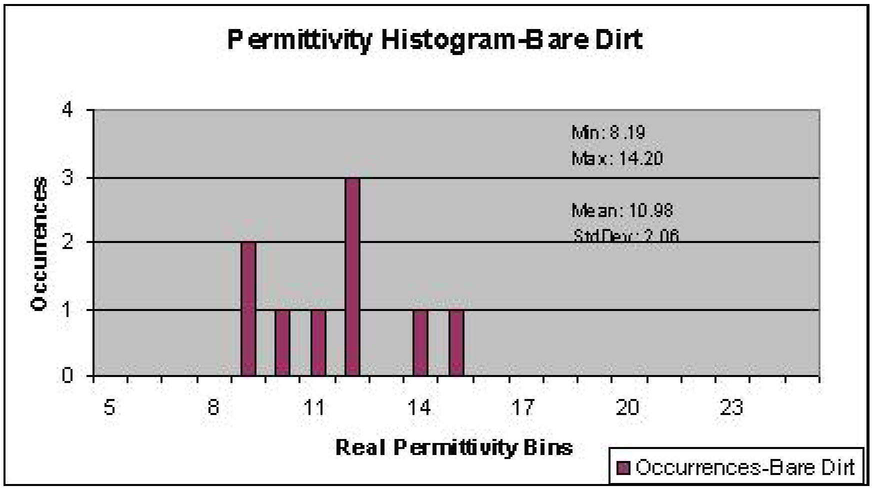

Figure 38. Permittivity histogram for bare dirt.

8.3.2 Short Grass Environment

The variability of the soil measurements from the short grass was examined. The short grass environment is composed of sites 4, 6, and 7. Site 4 did not contain any mines (background) while sites 6 and 7 contained mines. The permittivity, conductivity, and water content measurements from these sites are contained in Table 6.

Table 6. Comparison of mines and background short grass environment.

Site	Date	Area Description	Real ε Avg.	Imag ε Avg.	σ Avg.	H_2O (g/cm^3)
6	21 Oct 2002	Mine, short grass	10.22	1.39	0.107	0.1915
6	29 Oct 2002	Mine, short grass	12.28	1.67	0.126	0.2269
6	25 Nov 2002	Mine, short grass	8.28	1.09	0.081	0.1557
7	21 Oct 2002	Mine, short grass	14.67	1.82	0.157	0.2796
7	29 Oct 2002	Mine, short grass	17.38	2.23	0.199	0.3231
7	25 Nov 2002	Mine, short grass	12.21	1.61	0.125	0.2436
4	21 Oct 2002	Bkgrd, short grass	13.95	1.57	0.133	0.2670
4	29 Oct 2002	Bkgrd, short grass	16.41	1.57	0.145	0.2858
4	25 Nov 2002	Bkgrd, short grass	19.43	1.98	0.182	0.3373

Background sample (site 4) measurement results were between those of sites 6 and 7 on 21 and 29 October 2002. This was not the case for samples taken on 25 November 2002. For these samples, site 4 had the greatest water content. The driest samples were collected from sites 6 and 7 on 25 November 2002, which was expected (Table 2). However, the sample collected from site 4 on 25 November 2002 had the greatest water content of all the samples taken in the short grass, which was not expected because the soil was drying for at least 72 hr. Although the parameters measured at site 4 should not be used in modeling the targets, it may be useful in characterizing the clutter backscatter.

The average conductivity and permittivity at sites 4, 6, and 7 increased with increasing water content. Notice that the average permittivity imaginary component at site 4 on 21 and 29 October 2002 are the same. Again, this may be due to the tolerance of the Damaskos system.

A permittivity histogram of the short grass environment is contained in Figure 39. The bins are based on the average permittivity real component values.

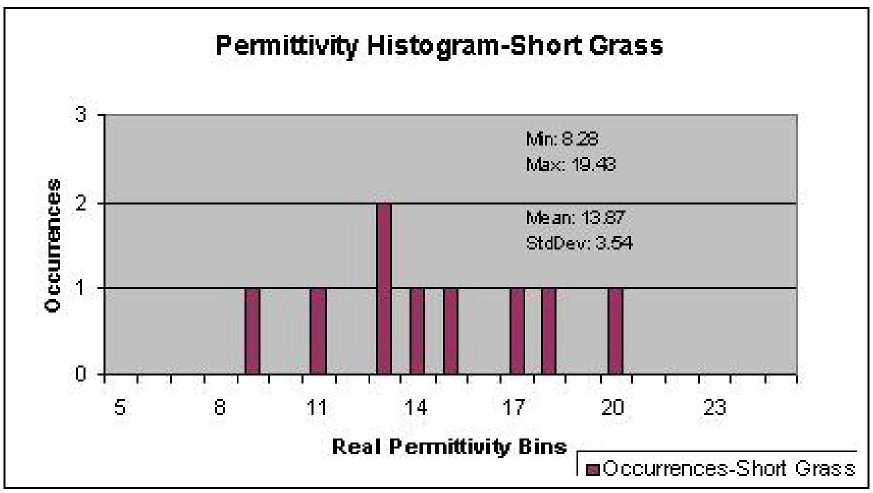

Figure 39. Permittivity histogram for the short grass environment.

8.3.3 Tall Grass Environment

The tall grass environment is composed of sites 5, 8, 9 and 10. Site 5 did not contain any mines (background) while sites 8 through 10 contained mines. The permittivity, conductivity, and water content measurements from these sites are contained in Table 7.

Table 7. Comparison of mines and background tall grass environment.

Site	Date	Area Description	Real ε Avg.	Imag ε Avg.	σ Avg.	H_2O (g/cm^3)
8	21 Oct 2002	Mine, tall grass	9.66	1.62	0.115	0.1793
8	29 Oct 2002	Mine, tall grass	12.45	2.25	0.157	0.2071
8	25 Nov 2002	Mine, tall grass	6.59	0.94	0.065	0.1188

Table 7. Comparison of mines and background tall grass environment (cont'd).

Site	Date	Area Description	Real ε Avg.	Imag ε Avg.	σ Avg.	H_2O (g/cm^3)
9	21 Oct 2002	Mine, tall grass	14.27	2.26	0.174	0.2503
9	29 Oct 2002	Mine, tall grass	16.22	2.60	0.202	0.2888
9	25 Nov 2002	Mine, tall grass	16.21	3.14	0.232	0.2740
10	21 Oct 2002	Mine, tall grass	15.13	1.62	0.135	0.2438
10	29 Oct 2002	Mine, tall grass	24.00	3.55	0.309	0.3868
10	25 Nov 2002	Mine, tall grass	23.36	3.80	0.328	0.3574
5	21 Oct 2002	Bkgrd, tall grass	10.80	1.56	0.116	0.2005
5	29 Oct 2002	Bkgrd, tall grass	13.40	1.78	0.134	0.2225
5	25 Nov 2002	Bkgrd, tall grass	8.78	1.14	0.084	0.1650

Results reveal that the soil samples from the background site (site 5) always had lower water content then sample sites 9 and 10. With regard to site 8, site 5 always had higher water content. The driest samples were collected from sites 8 and 5 on 25 November 2002, which was expected (Table 2). Site 10 typically had the most water, which was expected because this was the lowest point in the tall grass area and water tended to pool there. Although the parameters measured at site 5 should not be used in modeling the targets, it may be useful in characterizing the clutter backscatter.

The conductivity and permittivity at sites 5 and 8 increased with increasing water content. The average permittivity real values at sites 9 and 10 also increased with increasing water content. However, this was not the case for the conductivity and imaginary permittivity components at sites 9 and 10. Again, this may be due to the measurement error of the Damaskos system.

A permittivity histogram of the tall grass environment is contained in Figure 40.

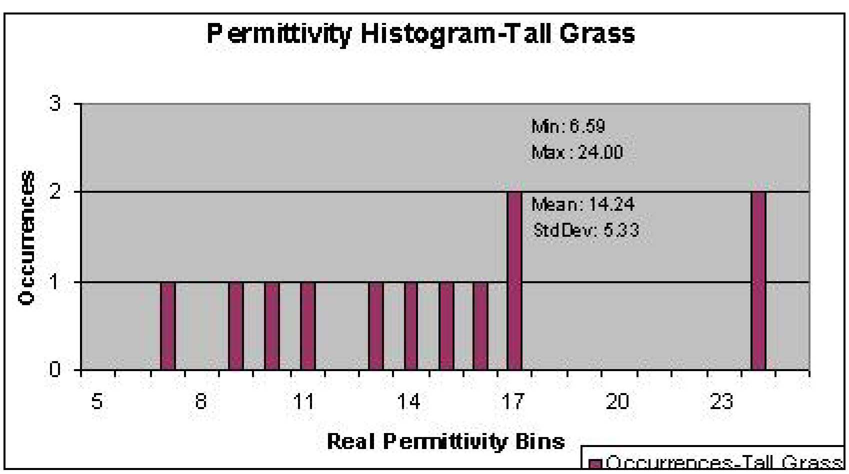

Figure 40. Permittivity histogram for the tall grass environment.

Figure 41 combines the bins from the bare dirt, short grass, and tall grass environments. In essence, this is the drop zone area. The minimum, maximum, mean, and standard deviation values, contained in Figure 41, are based on the real permittivity average values from the bare dirt, short grass, and tall grass environments.

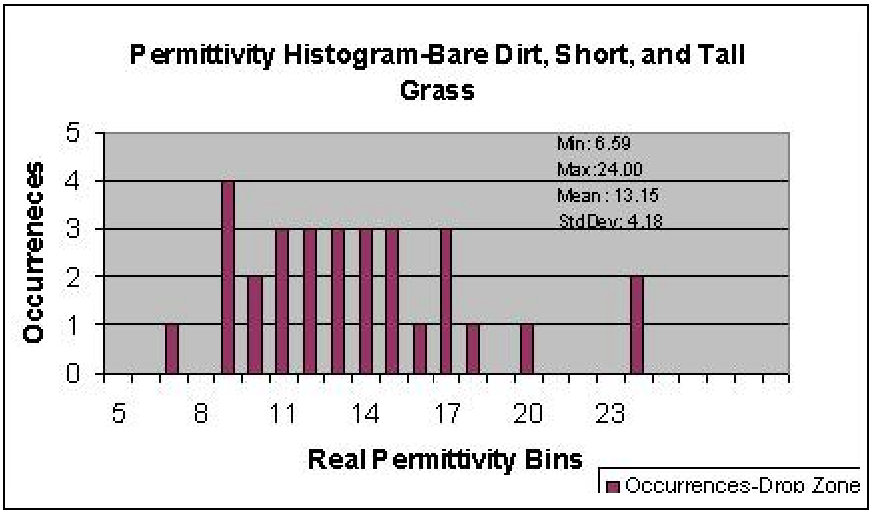

Figure 41. Permittivity histogram for the drop zone (bare dirt, short, and tall grass).

8.4 Max–Min Permittivity of Bare Dirt, Short, and Tall Grass Environments

The average water content and delta (Δ) (difference between the maximum and minimum water content) of the bare dirt, short grass, and tall grass are contained in Table 8. The water content averages for the bare dirt and short grass are based on nine samples while the tall grass average is based on 12 samples. The Δ's were calculated by subtracting the max water content from the min water content for each environment. The short grass environment had the highest average water content; however, the tall grass environment had the largest Δ between samples and the most extreme max and min water content values. The comparison between the maximum and minimum real permittivity for the bare dirt, short, and tall grass environments are contained in Figure 42. The solid black line represents the maximum real permittivity for the tall grass environment, while the dotted black line denotes the minimum real permittivity for the tall grass environment. The red lines correspond to the short grass environment and the blue lines correspond to the bare dirt environment. As can be seen, the more moisture contained in the soil, the higher the real component of the permittivity.

Table 8. Average water content of drop zone test environments.

Environment	Water Content Avg. (g/cm^3)	Max Content (g/cm^3)	Min Content (g/cm^3)	Δ (Max–Min) (g/cm^3)
Bare dirt	0.2152	0.2726	0.1459	0.1267
Short grass	0.2567	0.3373	0.1557	0.1816
Tall grass	0.2412	0.3868	0.1188	0.2680

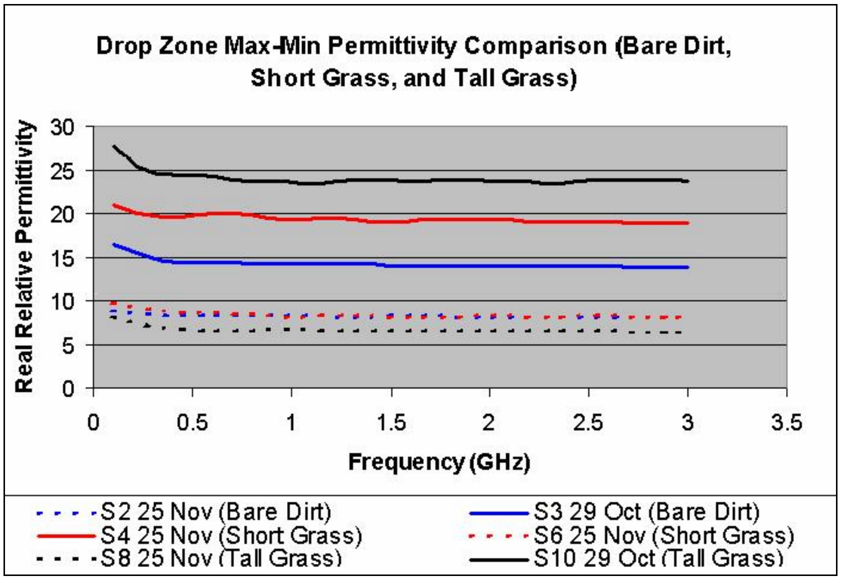

Figure 42. Drop zone max-min permittivity comparison.

8.5 Rainfall Effect on Bare Dirt

As noted earlier, average permittivity real component values increased with increasing water content for measurements made on the same type of soil. It would be beneficial to be able to form a correlation between historical site rainfall and the current soil moisture content. Figure 43 plots five different columns of amplitude data vs. time in days. The light blue bars shown in the background represent a weighted running daily rainfall average where the running average is calculated by adding up the rainfall of all days from the beginning of October 2002 to the current day shown on the graph and then dividing by the number of days used during the summation. The weight is an average of the rainfall during the four days prior to and inclusive of the current day on the graph. This five-day average is then added to the running average. The theory is that the prior four days' and the current day's rainfall have a greater influence on the current soil moisture content than rainfall which occurred more than five days prior. For this particular location, the actual numbers work out well, but we do not conclude that this model is applicable to all soils and historical weather conditions. The dark blue bars represent actual rainfall, and the red, yellow, and purple bars represent permittivity measurements in the bare dirt areas (sites 1, 2, and 3). The permittivity values are the real relative values. All of the bars, except actual rainfall, have been scaled to fit the graph vertical (z) axis. This graph is presented as a coarse correlation method only.

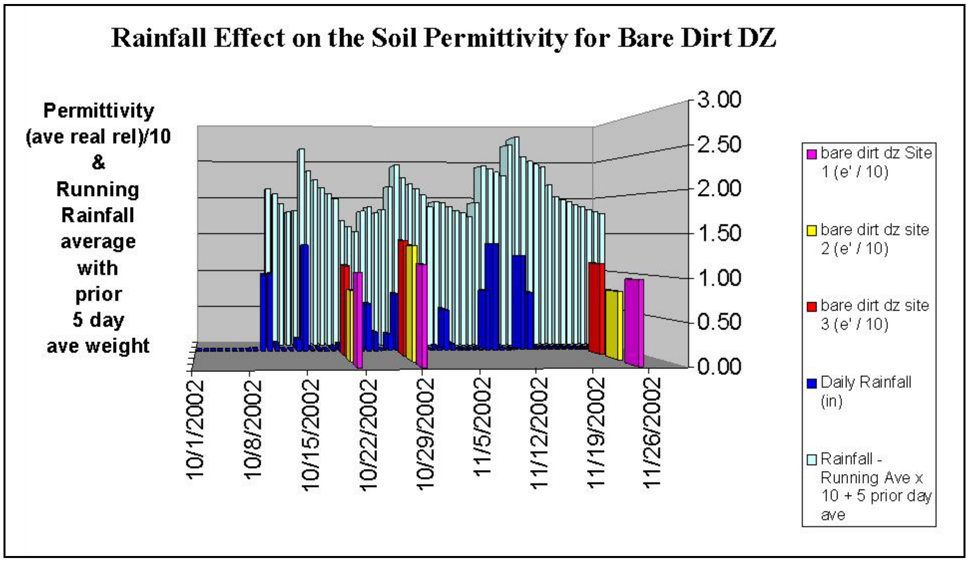

Figure 43. Rainfall effect on the bare dirt.

8.6 LAMD and Area 71A Environments

The variability of the soil measurements from the LAMD and Area 71A sites were examined. The LAMD environment is composed of sites 11, 12, 13, and 14. Sites 15 and 16 are contained in Area 71A, lane 19. All of these sites contained mines. The permittivity, conductivity, and water content measurements from these sites are contained in Table 9.

Table 9. Comparison of LAMD and Area 71A, lane 19 environments.

Site	Date	Area Description	Real ε Avg.	Imag ε Avg.	σ Avg.	H_2O (g/cm^3)
		LAMD				
11	21 Oct 2002	Mine, sand/stones	6.46	0.57	0.043	0.1000
11	29 Oct 2002	Mine, sand/stones	7.14	0.61	0.048	0.1146
11	25 Nov 2002	Mine, sand/stones	5.05	0.41	0.029	0.0771
12	21 Oct 2002	Mine, sand	14.78	1.98	0.156	0.2630
12	29 Oct 2002	Mine, sand	17.45	2.14	0.169	0.2973
12	25 Nov 2002	Mine, sand	15.67	1.99	0.154	0.2688
13	21 Oct 2002	Mine, tall grass	14.95	1.90	0.166	0.3173
13	29 Oct 2002	Mine, tall grass	21.24	2.74	0.237	0.3915
13	25 Nov 2002	Mine, tall grass	16.73	2.42	0.192	0.3239
14	21 Oct 2002	Mine, gravel	7.36	0.90	0.066	0.1014
14	29 Oct 2002	Mine, gravel	7.78	0.93	0.070	0.1074
14	25 Nov 2002	Mine, gravel	6.20	0.73	0.051	0.0864

Table 9. Comparison of LAMD and Area 71A, lane 19 environments (cont'd).

Site	Date	Area Description	Real ε Avg.	Imag ε Avg.	σ Avg.	H_2O (g/cm^3)
Area 71A						
15	21 Oct 2002	Mine, gravel	7.66	0.95	0.070	0.1073
15	29 Oct 2002	Mine, gravel	16.39	1.95	0.164	0.2257
15	25 Nov 2002	Mine, gravel	6.60	0.77	0.055	0.0976
16	21 Oct 2002	Mine, clay	11.91	1.18	0.099	0.2157
16	29 Oct 2002	Mine, clay	15.97	1.61	0.138	0.2652
16	25 Nov 2002	Mine, clay	11.35	1.22	0.103	0.2112

The average conductivity and permittivity at sites 11, 13, 14, and 15 increased with increasing water content. Average permittivity real values at sites 12 and 16 also increased with increasing water content. However, this was not the case for the site 12 and 16 conductivity and site 16 average imaginary permittivity values. This may be due to the measurement error of the Damaskos system.

The LAMD and Area 71A statistics, shown in Table 10, are based on three samples for each environment.

Table 10. Soil measurement statistics.

Location	Minimum	Maximum	Mean	Std Dev
LAMD				
Sand/stones	5.05	7.14	6.22	1.07
Sand	14.78	17.45	15.97	1.36
Tall grass	14.95	21.24	17.64	3.24
Gravel	6.20	7.78	7.11	0.82
Area 71A				
Gravel	6.60	16.39	10.22	5.37
Clay	11.35	15.97	13.08	2.52

8.7 Tailored Data

Table 11 results are tailored to the SRI radar (200–450 MHz) and are based on measurements from 194.25 to 455.25 MHz. Table 12 results are tailored to the Mirage radar (300–2800 MHz) and are based on measurements from 295.75 to 2804.25 MHz. The Veridian radar (8.16–10 GHz) exceeded the operational frequency range of the Damaskos system; hence, there are no tailored results.

Table 11. Permittivity and conductivity measurements from 194.25 to 455.25 MHz.

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
1	21 Oct 2002	11.1–11.4	11.25	1.3–2.2	1.53	0.02–0.03	0.027	0.2207
1	29 Oct 2002	12.0–12.3	12.21	1.4–2.3	1.60	0.02–0.04	0.028	0.2227
1	25 Nov 2002	9.8–10.6	10.15	1.3–2.3	1.77	0.025–0.033	0.031	0.1994
2	21 Oct 2002	8.3–8.9	8.63	0.6–0.9	0.76	0.01–0.02	0.014	0.1520
2	29 Oct 2002	13.6–14.3	13.86	1.0–1.6	1.26	0.017–0.024	0.022	0.2285
2	25 Nov 2002	8.2–8.5	8.39	0.6–0.9	0.72	0.01–0.02	0.013	0.1459
3	21 Oct 2002	11.2–11.8	11.46	1.2–1.9	1.61	0.02–0.03	0.028	0.2475
3	29 Oct 2002	14.4–15.5	14.76	1.7–2.8	2.28	0.030–0.044	0.040	0.2726
3	25 Nov 2002	11.4–12.4	11.79	1.3–2.3	1.87	0.02–0.04	0.033	0.2478
4	21 Oct 2002	13.8–15.3	14.16	1.4–3.1	2.17	0.03–0.04	0.036	0.2670
4	29 Oct 2002	16.5–17.2	16.64	1.1–2.0	1.56	0.02–0.03	0.027	0.2858
4	25 Nov 2002	19.7–20.8	19.94	1.5–2.7	1.95	0.03–0.04	0.033	0.3373
5	21 Oct 2002	11.3–12.2	11.60	1.9–3.3	2.50	0.04–0.05	0.043	0.2005
5	29 Oct 2002	13.5–14.9	13.97	2.2–4.1	3.07	0.04–0.06	0.053	0.2225
5	25 Nov 2002	9.0–9.8	9.34	1.5–2.6	1.97	0.03–0.04	0.034	0.1650
6	21 Oct 2002	10.5–11.3	10.76	1.6–2.9	2.20	0.03–0.04	0.038	0.1915
6	29 Oct 2002	12.3–13.9	12.80	2.0–3.8	2.96	0.04–0.06	0.051	0.2269
6	25 Nov 2002	8.5–9.2	8.82	1.4–2.3	1.80	0.025–0.034	0.031	0.1557
7	21 Oct 2002	15.3–15.9	15.45	1.7–2.5	1.99	0.03–0.04	0.035	0.2796
7	29 Oct 2002	17.2–18.8	17.52	1.6–3.7	2.57	0.04–0.05	0.043	0.3231
7	25 Nov 2002	12.4–13.0	12.62	1.8–3.5	2.52	0.04–0.05	0.043	0.2436
8	21 Oct 2002	9.8–11.2	10.34	2.2–4.0	3.10	0.04–0.06	0.054	0.1793
8	29 Oct 2002	13.1–14.3	13.53	3.2–5.6	4.09	0.06–0.08	0.071	0.2071
8	25 Nov 2002	6.6–7.5	7.02	1.4–2.5	1.90	0.03–0.04	0.033	0.1188
9	21 Oct 2002	14.8–16.1	15.14	2.6–4.9	3.54	0.05–0.07	0.061	0.2503
9	29 Oct 2002	16.7–18.2	17.18	3.0–5.3	3.97	0.06–0.08	0.069	0.2888
9	25 Nov 2002	16.9–18.2	17.31	4.0–7.4	5.26	0.08–0.10	0.091	0.2740
10	21 Oct 2002	15.4–16.4	15.72	1.7–2.8	2.16	0.03–0.04	0.037	0.2438
10	29 Oct 2002	24.3–25.8	24.78	3.1–5.7	4.09	0.06–0.08	0.071	0.3868
10	25 Nov 2002	23.5–24.9	23.77	3.0–7.4	4.67	0.077–0.081	0.079	0.3574
11	21 Oct 2002	6.6–6.9	6.72	0.7–1.2	0.89	0.01–0.02	0.016	0.1000
11	29 Oct 2002	7.3–7.6	7.39	0.6–1.2	0.81	0.01–0.02	0.014	0.1146
11	25 Nov 2002	5.2–5.4	5.31	0.7–1.0	0.77	0.01–0.02	0.014	0.0771
12	21 Oct 2002	15.8–16.3	16.02	2.4–3.4	2.68	0.04–0.06	0.048	0.2630
12	29 Oct 2002	18.0–19.2	18.40	2.5–4.2	3.12	0.05–0.06	0.054	0.2973
12	25 Nov 2002	16.0–17.2	16.35	2.3–4.3	3.12	0.05–0.06	0.054	0.2688

Table 11. Permittivity and conductivity measurements from 194.25 to 455.25 MHz (cont'd).

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
13	21 Oct 2002	14.4–16.5	15.37	1.9–3.4	2.85	0.03–0.06	0.050	0.3173
13	29 Oct 2002	22.0–22.7	22.26	2.6–3.9	3.05	0.04–0.06	0.053	0.3915
13	25 Nov 2002	17.5–18.1	17.62	2.9–4.8	3.52	0.05–0.07	0.061	0.3239
14	21 Oct 2002	7.6–8.2	7.86	1.2–1.9	1.46	0.02–0.03	0.026	0.1014
14	29 Oct 2002	8.2–8.5	8.28	1.1–1.8	1.32	0.02–0.03	0.023	0.1074
14	25 Nov 2002	6.3–6.9	6.59	1.1–1.7	1.35	0.02–0.03	0.024	0.0864
15	21 Oct 2002	8.1–8.4	8.25	1.3–1.9	1.46	0.02–0.03	0.026	0.1073
15	29 Oct 2002	16.7–17.4	17.10	2.1–3.0	2.40	0.03–0.05	0.042	0.2257
15	25 Nov 2002	6.7–7.2	6.96	1.1–1.7	1.37	0.02–0.03	0.024	0.0976
16	21 Oct 2002	12.1–12.7	12.39	1.2–1.8	1.57	0.02–0.03	0.028	0.2157
16	29 Oct 2002	16.5–16.9	16.72	1.7–2.3	1.87	0.02–0.04	0.033	0.2652
16	25 Nov 2002	11.4–12.3	11.73	1.2–2.1	1.74	0.023–0.032	0.030	0.2112

Table 12. Permittivity and conductivity measurements from 295.75 to 2804.25 MHz.

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
1	21 Oct 2002	10.2–11.3	10.57	0.8–1.8	1.13	0.02–0.20	0.094	0.2207
1	29 Oct 2002	11.2–12.3	11.49	1.0–1.7	1.23	0.02–0.20	0.102	0.2227
1	25 Nov 2002	9.6–10.3	9.74	0.7–1.9	0.94	0.03–0.14	0.078	0.1994
2	21 Oct 2002	8.1–8.9	8.36	0.2–0.9	0.54	0.01–0.11	0.047	0.1520
2	29 Oct 2002	13.3–14.0	13.60	0.6–1.5	1.11	0.02–0.23	0.103	0.2285
2	25 Nov 2002	8.0–8.5	8.17	0.4–0.7	0.58	0.01–0.10	0.051	0.1459
3	21 Oct 2002	10.8–11.6	11.04	0.9–1.8	1.08	0.03–0.19	0.093	0.2475
3	29 Oct 2002	13.9–14.8	14.12	1.2–2.6	1.49	0.04–0.28	0.130	0.2726
3	25 Nov 2002	11.0–11.9	11.23	0.7–2.1	1.14	0.03–0.19	0.096	0.2478
4	21 Oct 2002	13.6–14.3	13.88	0.8–2.4	1.43	0.03–0.29	0.128	0.2670
4	29 Oct 2002	16.2–16.9	16.38	0.9–2.1	1.49	0.03–0.32	0.139	0.2858
4	25 Nov 2002	19.0–20.0	19.38	1.1–2.6	1.88	0.03–0.40	0.175	0.3373
5	21 Oct 2002	10.5–11.6	10.72	1.0–2.6	1.42	0.04–0.22	0.114	0.2005
5	29 Oct 2002	13.0–13.9	13.31	1.2–3.3	1.60	0.05–0.25	0.133	0.2225
5	25 Nov 2002	8.4–9.4	8.71	0.8–2.1	1.02	0.03–0.16	0.082	0.1650
6	21 Oct 2002	9.9–10.8	10.15	1.0–2.4	1.26	0.04–0.21	0.104	0.1915
6	29 Oct 2002	12.0–12.8	12.18	1.0–3.3	1.50	0.05–0.24	0.123	0.2269
6	25 Nov 2002	8.0–8.9	8.22	0.7–1.9	0.98	0.03–0.16	0.078	0.1557
7	21 Oct 2002	14.2–15.4	14.60	1.3–2.2	1.71	0.03–0.34	0.150	0.2796
7	29 Oct 2002	16.9–17.9	17.31	1.2–2.8	2.07	0.04–0.42	0.194	0.3231
7	25 Nov 2002	11.9–12.6	12.17	0.9–2.7	1.45	0.04–0.25	0.123	0.2436

Table 12. Permittivity and conductivity measurements from 295.75 to 2804.25 MHz (cont'd).

Site	Date	Real ε Min–Max	Real ε Avg.	Imag ε Min–Max	Imag ε Avg.	σ Min–Max	σ Avg.	H_2O (g/cm^3)
8	21 Oct 2002	9.3–10.5	9.55	1.0–3.3	1.44	0.05–0.21	0.112	0.1793
8	29 Oct 2002	12.0–13.6	12.32	1.6–4.2	2.02	0.07–0.25	0.156	0.2071
8	25 Nov 2002	6.4–7.1	6.53	0.6–2.0	0.83	0.03–0.13	0.065	0.1188
9	21 Oct 2002	13.8–15.0	14.17	1.6–3.7	2.05	0.06–0.33	0.169	0.2503
9	29 Oct 2002	15.7–17.2	16.10	1.8–4.2	2.36	0.07–0.40	0.197	0.2888
9	25 Nov 2002	15.5–17.3	16.09	2.4–5.4	2.82	0.09–0.43	0.229	0.2740
10	21 Oct 2002	14.8–15.7	15.06	1.2–2.3	1.50	0.04–0.29	0.130	0.2438
10	29 Oct 2002	23.2–24.8	23.86	2.4–4.3	3.31	0.07–0.67	0.297	0.3868
10	25 Nov 2002	22.6–24.1	23.26	2.6–4.7	3.48	0.08–0.69	0.317	0.3574
11	21 Oct 2002	6.3–6.7	6.43	0.4–0.9	0.52	0.01–0.08	0.042	0.1000
11	29 Oct 2002	7.0–7.4	7.11	0.5–0.8	0.56	0.01–0.10	0.047	0.1146
11	25 Nov 2002	4.9–5.3	5.02	0.2–0.8	0.37	0.01–0.06	0.028	0.0771
12	21 Oct 2002	14.3–16.1	14.68	1.2–2.8	1.85	0.04–0.30	0.153	0.2630
12	29 Oct 2002	16.9–18.4	17.34	1.3–3.2	1.96	0.05–0.34	0.164	0.2973
12	25 Nov 2002	15.3–16.3	15.56	1.4–3.2	1.79	0.05–0.29	0.149	0.2688
13	21 Oct 2002	14.4–15.8	14.86	0.3–3.4	0.175	0.01–0.37	0.159	0.3173
13	29 Oct 2002	20.6–22.2	21.16	1.8–3.2	2.59	0.05–0.49	0.229	0.3915
13	25 Nov 2002	16.4–17.6	16.66	1.6–3.6	2.20	0.06–0.39	0.186	0.3239
14	21 Oct 2002	7.1–7.9	7.31	0.6–1.5	0.83	0.03–0.11	0.066	0.1014
14	29 Oct 2002	7.5–8.3	7.74	0.7–1.3	0.87	0.02–012	0.069	0.1074
14	25 Nov 2002	6.0–6.7	6.16	0.4–1.4	0.65	0.02–0.09	0.050	0.0864
15	21 Oct 2002	7.4–8.3	7.61	0.7–1.4	0.88	0.02–0.12	0.070	0.1073
15	29 Oct 2002	16.1–17.3	16.33	1.5–2.5	1.83	0.04–0.33	0.160	0.2257
15	25 Nov 2002	6.4–7.0	6.55	0.3–1.4	0.68	0.02–0.13	0.052	0.0976
16	21 Oct 2002	11.6–12.5	11.86	0.7–1.7	1.10	0.03–0.21	0.095	0.2157
16	29 Oct 2002	15.7–16.8	15.91	1.2–2.0	1.53	0.03–0.29	0.133	0.2652
16	25 Nov 2002	11.1–11.7	11.29	0.7–1.9	1.12	0.03–0.23	0.099	0.2112

9. Conclusions

A roll-off in the relative permittivity data is expected between 100 and 500 MHz (see section 8.1).

Increases in water per unit volume results in increased permittivity (see section 8.1).

Water content is not the sole factor influencing soil sample permittivity; soil composition plays a role (see section 8.2).

The average permittivity imaginary component does not always increase with increasing water content (see section 8.3.3).

The average conductivity does not always increase with increasing water content (see section 8.3.3).

Good estimates for the real part of the permittivity for the various test environments are summarized in Table 13 (see sections 8.3.1, 8.3.2, 8.3.3, and 8.6).

Table 13. Soil measurement estimates.

Location	Minimum	Maximum	Mean	Std Dev
Drop Zone				
Bare dirt	8.19	14.20	10.98	2.06
Short grass	8.28	19.43	13.87	3.54
Tall grass	6.59	24.00	14.24	5.33
LAMD				
Sand/stones	5.05	7.14	6.22	1.07
Sand	14.78	17.45	15.97	1.36
Tall grass	14.95	21.24	17.64	3.24
Gravel	6.20	7.78	7.11	0.82
Area 71A				
Gravel	6.60	16.39	10.22	5.37
Clay	11.35	15.97	13.08	2.52

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